“High density QCD with heavy-ions” [CMS capabilities at the LHC]

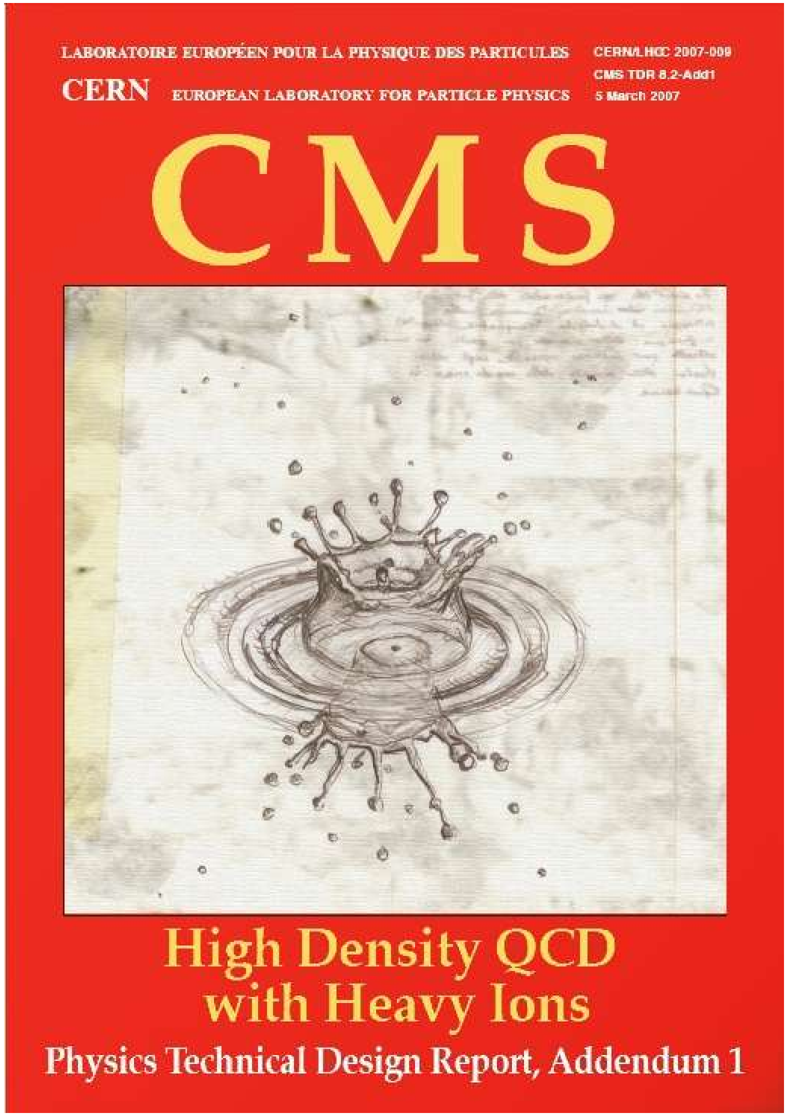
$5^{\text{èmes(!)}}$ Rencontres PQG-France

Etretat, 18 Sept 2007

David d'Enterria

CERN, PH-EP

"High density QCD with heavy-ions"



D.d'E (ed.) CERN-LHCC-2007-009; J.Phys.G. to appear.

- 170 pages
- 10 chapters
- ~90 figures, ~20 tables
- ~20 CMS-AN-Notes

- ~25 CMS-HI institutions
- ~100 collaborators

Moscow, Lyon, CERN, KFKI Budapest, Eötvös L. Budapest, Athens, Ioannina, Demokritos, Lisbon, Adana, MIT, Chicago, Los Alamos, Maryland, Minnesota, Iowa, UC Davis, Kansas, Mumbai, Auckland, Korea, Seoul, Chonbuk, Vanderbilt, Colorado, Zagreb

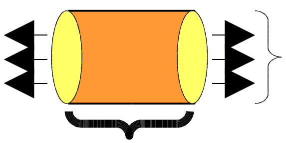
Overview

- Introduction – Physics Programme
  - Why high-energy nucleus-nucleus collisions ? at the LHC ? at CMS ?
- CMS capabilities to study many-body QCD (PbPb @ 5.5 TeV)
  - Case I: $dN_{ch}/d\eta \Rightarrow$ Colour-Glass-Condensate – gluon $xG_A(x,Q^2)$
  - Case II: Low p_T π/K/p spectra $\Rightarrow$ Hydrodynamics, Equation-of-State
  - Case III: Elliptic flow $\Rightarrow$ Hydrodynamics, QCD medium viscosity
  - Case IV: Hard-probes (triggering) $\Rightarrow$ thermodynam. & transport properties
  - Case V: "Jet quenching" $\Rightarrow$ Parton density, $\langle\hat{q}\rangle$ transport coefficient
  - Case VI: QQbar suppression $\Rightarrow \varepsilon_{crit}$, T_{crit}
  - Case VII: $\Upsilon \to e^+e^-, \mu^+\mu^-$ photoproduction in UPC PbPb $\Rightarrow$ CGC – $xG_A(x,Q^2)$
- Summary

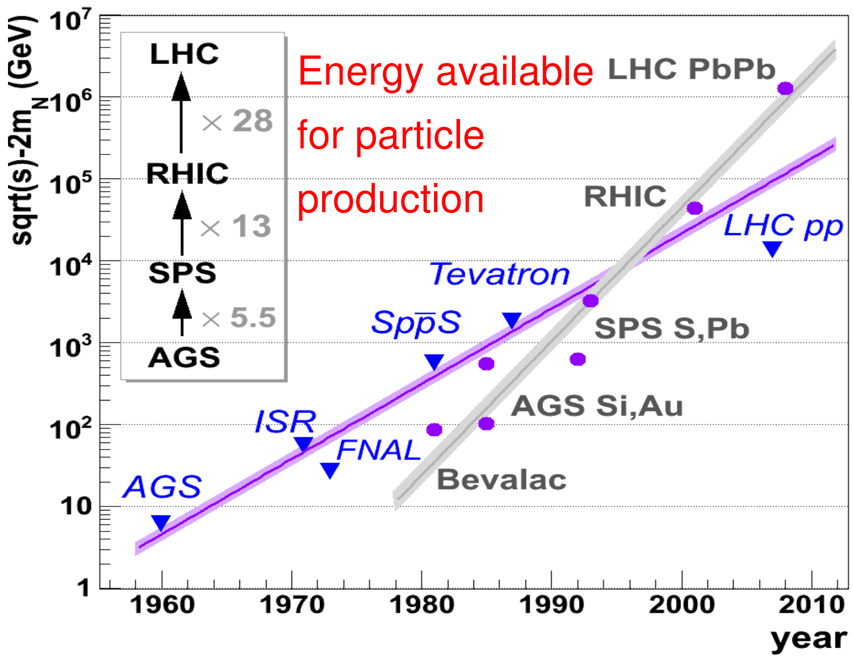
Energy densities in central AA collisions

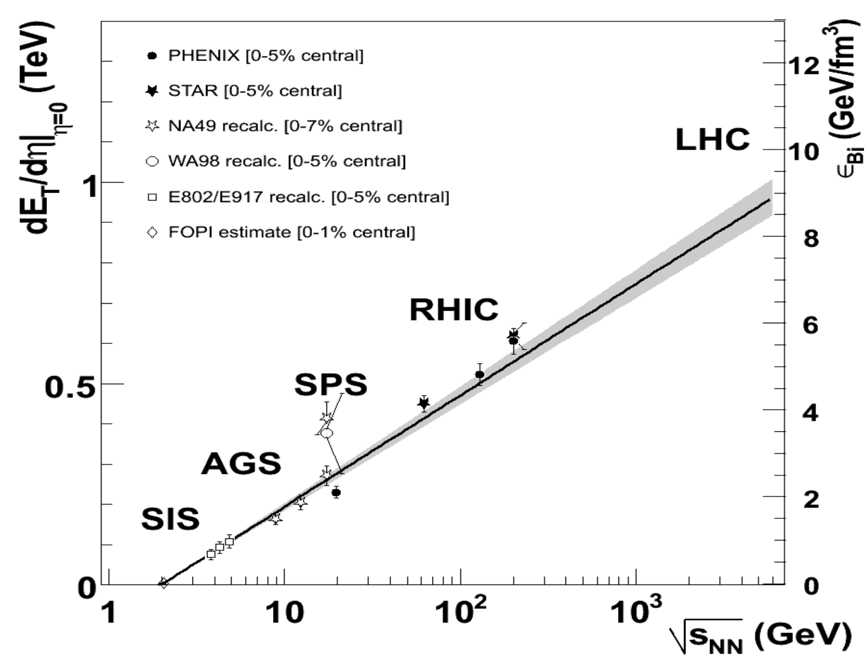
- T.D. Lee: *"In HEP we've concentrated on experiments in which we distribute a higher & higher amount of energy into a region with smaller & smaller dimensions. In order to study the question of 'vacuum', we must turn to a different direction; we should investigate 'bulk' phenomena by distributing high energy over a relatively large volume."* [Rev.Mod.Phys.47(1975)267]
- Energy density: "Bjorken estimate" (for a longitudinally expanding plasma):

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$



$\tau_0 \sim 1$ fm/c >> $\tau^{LHC}_{cross} = 2R/\gamma c \sim 5\cdot 10^{-3}$ fm/c



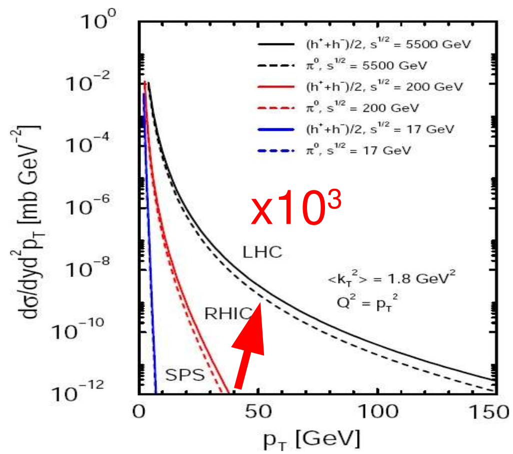


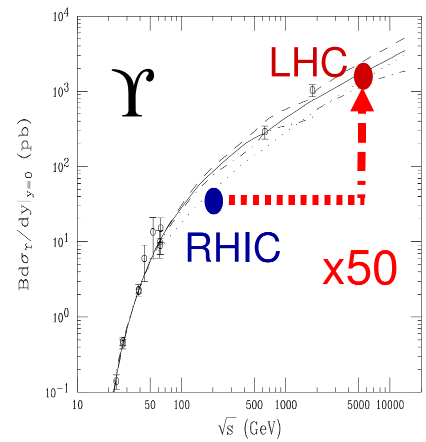
LHC: new frontier for QGP/CGC studies

- Produced quark-gluon matter:
  hotter, denser, bigger, longer-lived

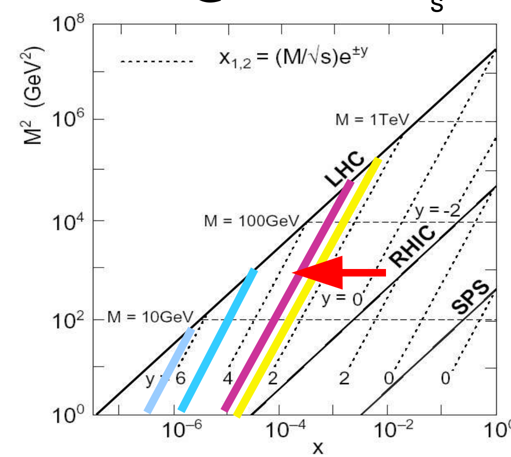
	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	X 28
dN_{ch}/dy	500	850	1500-3000	x 2-3
τ^0_{QGP} (fm/c)	1	0.2	0.1	faster
T/T_c	1.1	1.9	3.0-4.2	hotter
ε (GeV/fm^3)	3	5	15-60	denser
τ_{QGP} (fm/c)	≤2	2-4	≥10	longer
τ_f (fm/c)	~5	~10	~20	longer
V_f (fm^3)	few 10^3	few 10^4	few 10^5	bigger

- Very large pQCD cross-sections
  (“tomographic” probes of QCD medium)



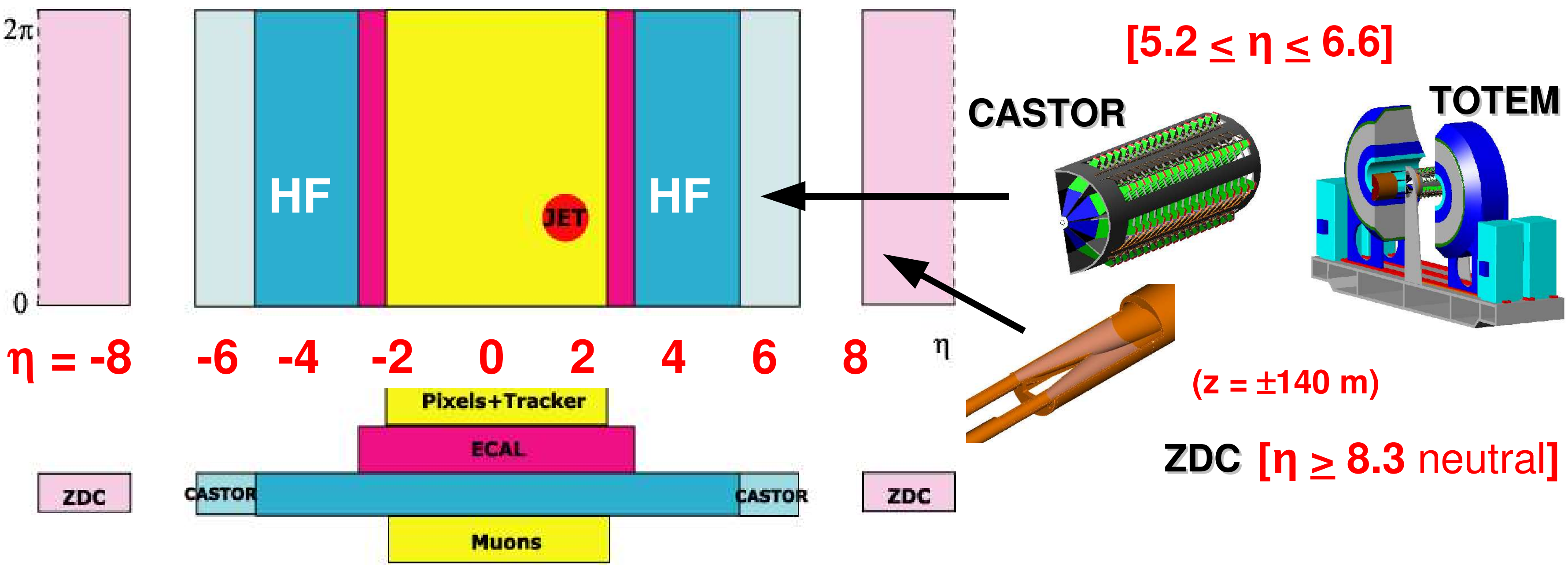


- Very low-x: $x=2p_T/\sqrt{s}$~10^{-4}-10^{-5} i.e. x30-45 smaller than @ RHIC. Q_s^2 ~ ×3 larger



CMS detector

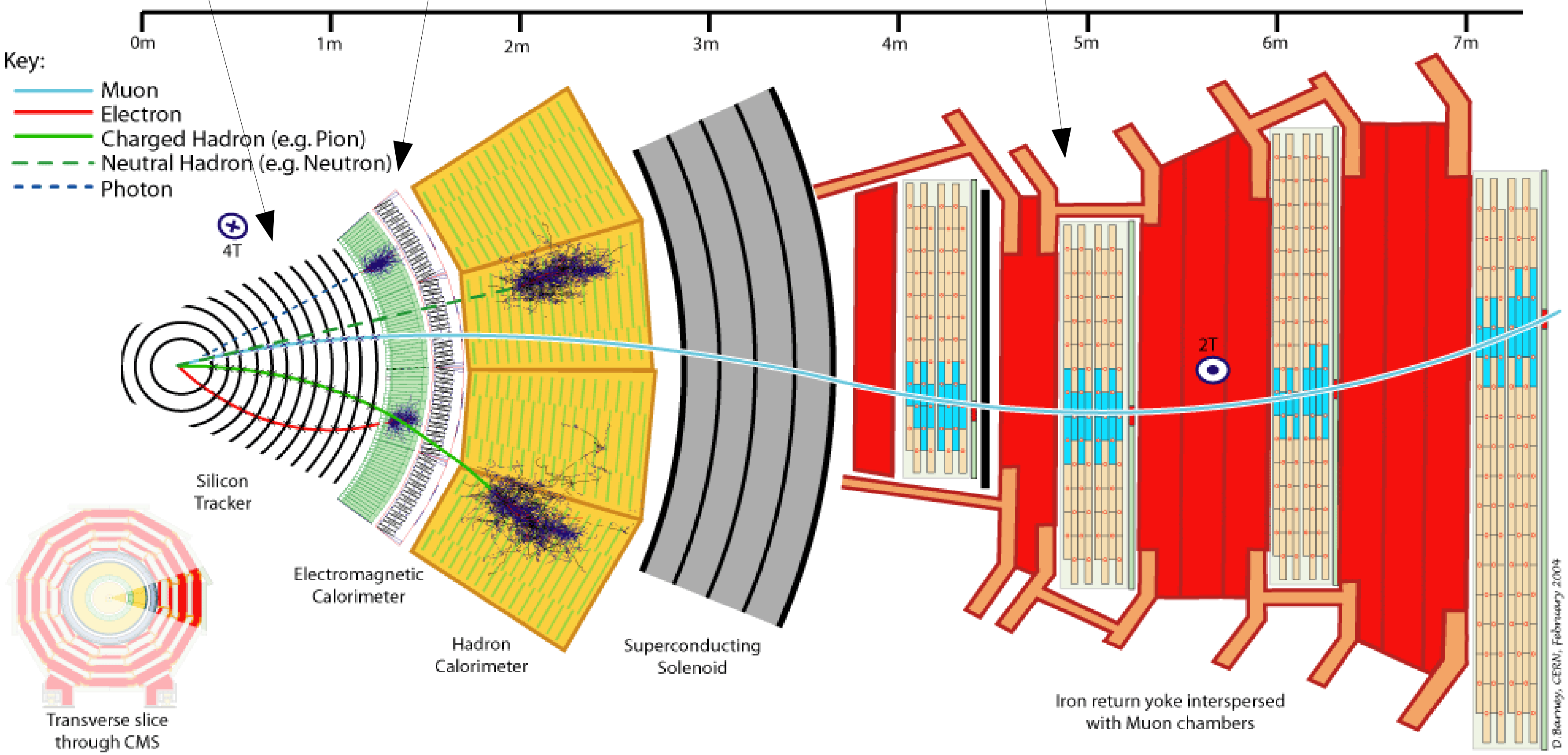
- CMS (incl. HF,CASTOR,ZDC) + TOTEM: quasi-full acceptance @ LHC



- Excellent pp, PbPb, pPb detection capabilities:
  - tracks, muons ($|\eta| \leq 2.5$, full φ) electrons/photons ($|\eta| \leq 3.$, full φ)
  - jets, particle/energy flow within $|\eta| \leq 6.7$ (and $\eta \geq 8.1$, neutral), full φ
  - very good precision/granularity/resolution.
  - large bandwidth DAQ/High-Level-Trigger

h±, e±, γ, μ± measurement in CMS (|η|<2.5)

Tracking + ECAL + muon-chambers



<u>Si TRACKER</u>

Silicon Microstrips and Pixels

<u>CALORIMETERS</u>

ECAL $PbWO_4$

HCAL Plastic Sci/Steel sandwich

<u>MUON BARREL</u>

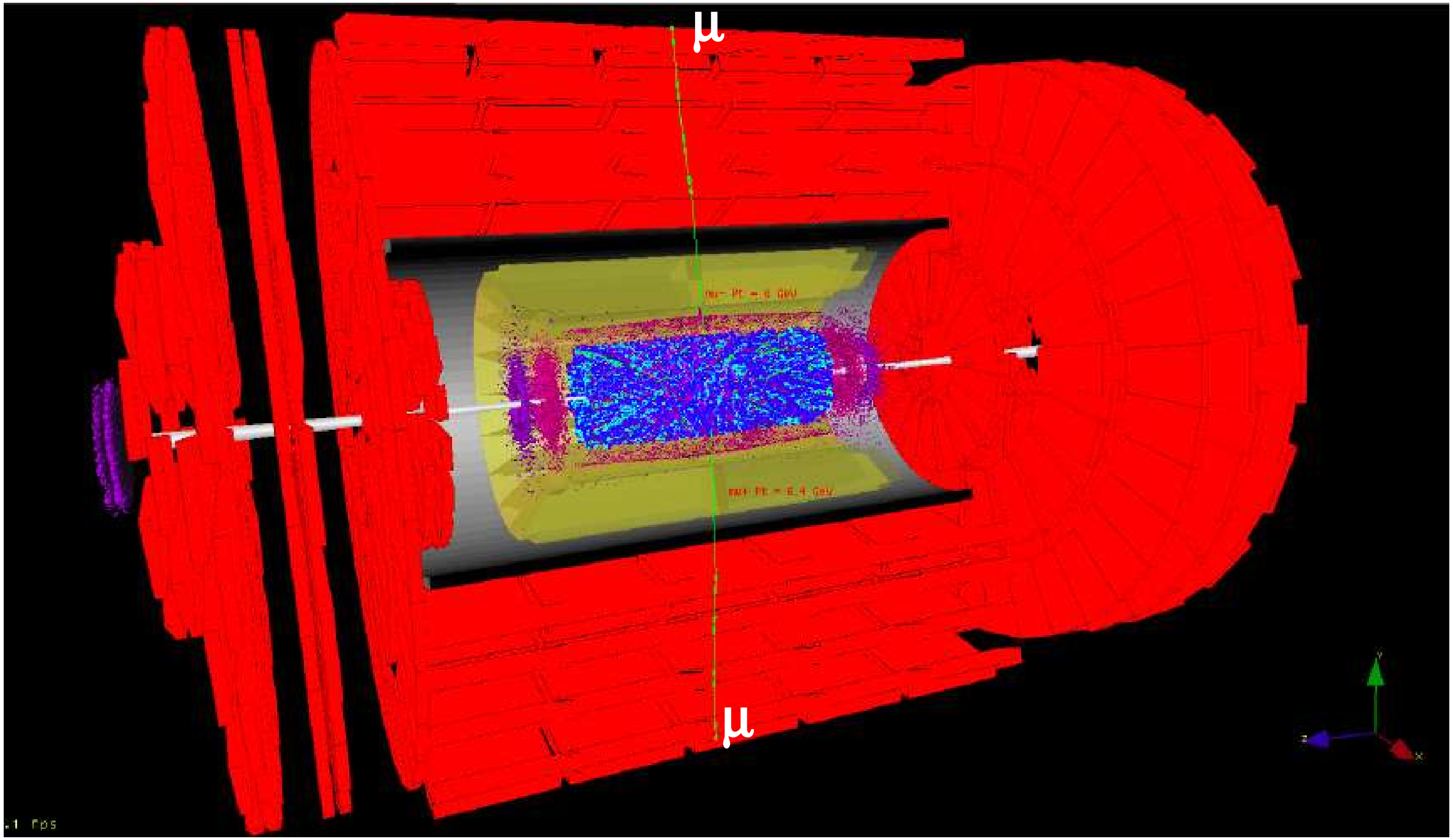
Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

PbPb → Υ+*X* event in CMS

All Pb-Pb results obtained within official (p-p) CMS software/simulation framework

Pb+Pb event ($dN_{ch}/d\eta$ = 3500) with $\Upsilon \rightarrow \mu^+\mu^-$



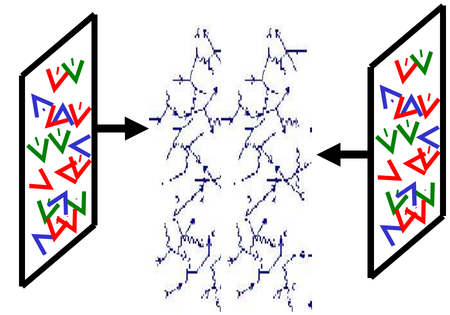
Case-Study I:
Total hadron multiplicity

Total PbPb hadron multiplicity (CMS)

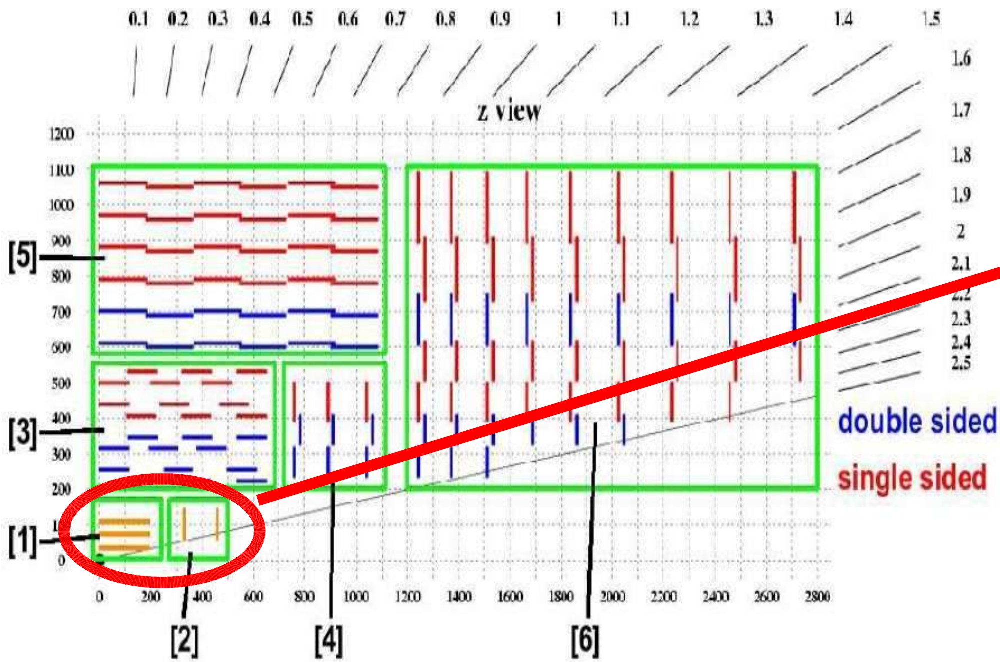
- Final A+A multiplicity ∝ Initial number of released gluons :

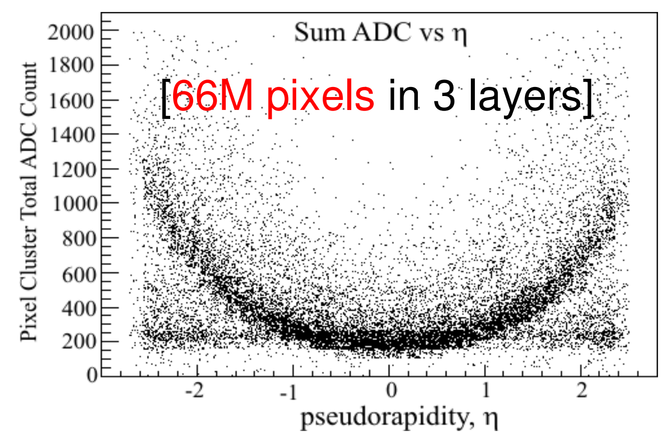
CGC: $$\frac{dN}{d^2b\,d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x, Q_s^2) \cdot A^{1/3}$$

\+ "local parton-hadron duality" (*1 gluon = 1 final hadron*)



- $dN_{ch}/d\eta$ ($|\eta|<2.5$) measured via hit counting in Si pixels:





- ADC pulse height
- Occupancy<2% for $dN_{ch}/d\eta$=5000
- Corr. factor (measured→primary)~0.83

Total PbPb hadron multiplicity (CMS)

- Final A+A multiplicity ∝ Initial number of released gluons :

CGC: $$\frac{dN}{d^2b\,d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x,Q_s^2)\cdot A^{1/3}$$

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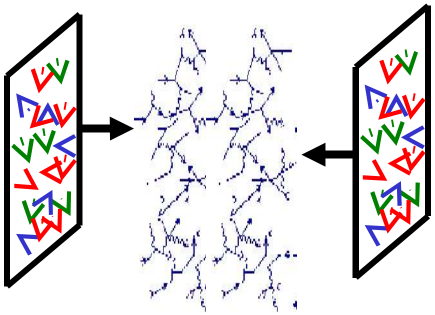

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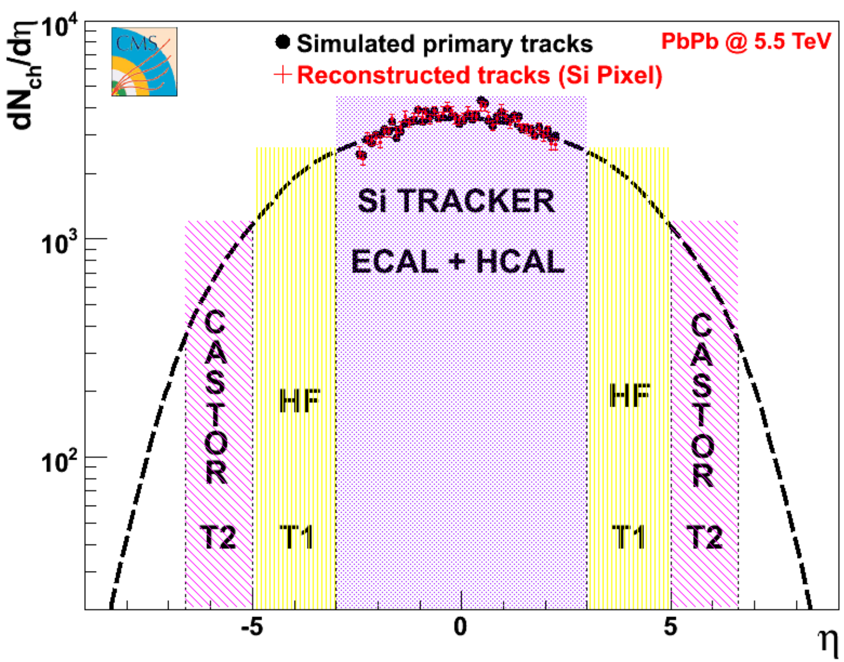
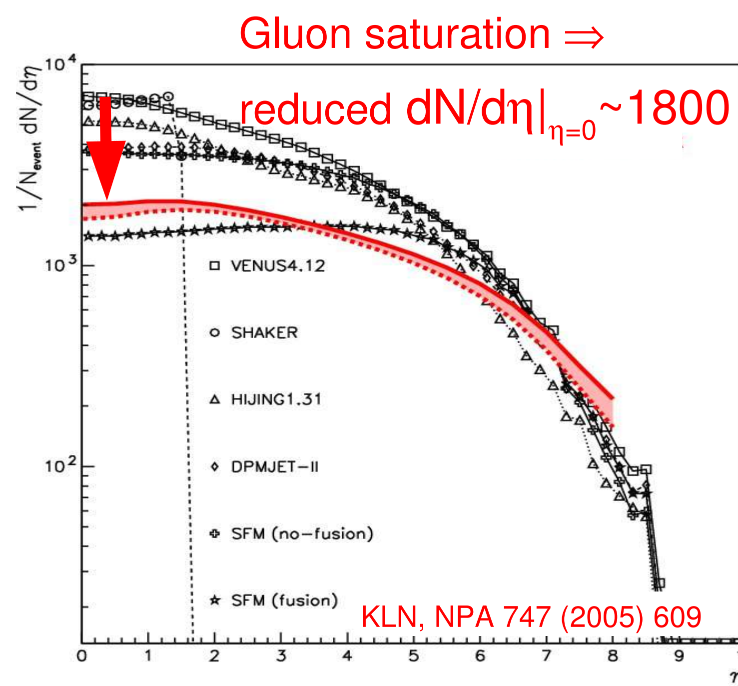
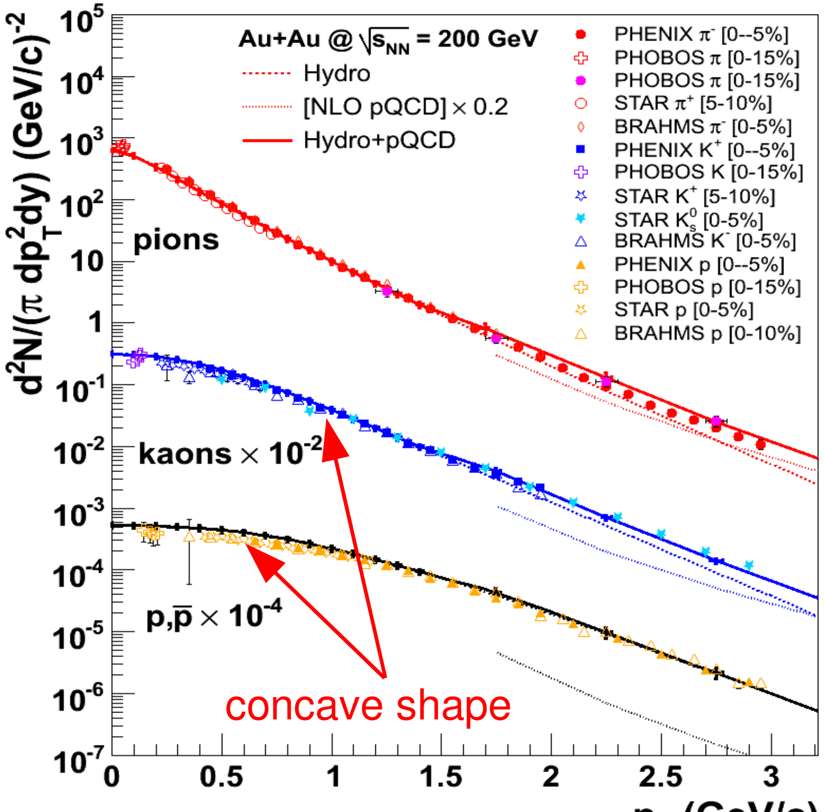




Case-Study II:
Soft hadron spectra

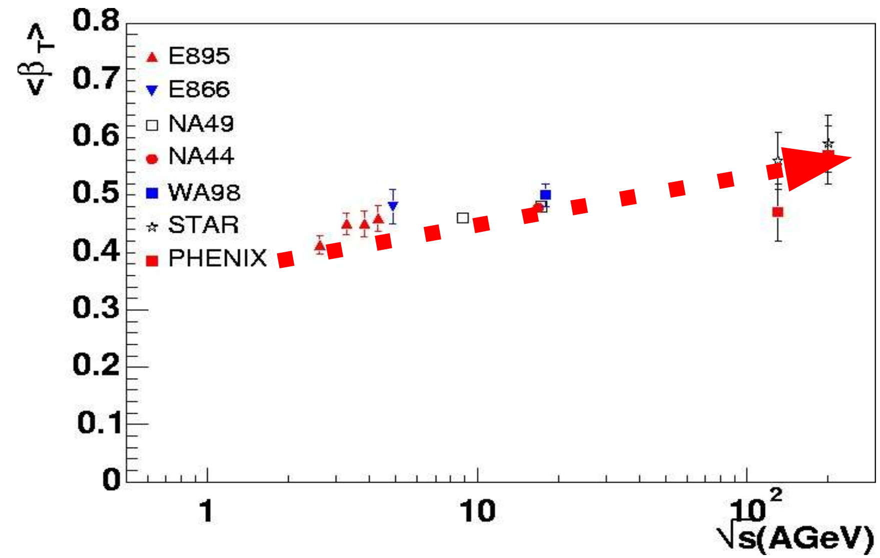
Soft hadron spectra (RHIC)

- Single hadron ($\pi^{\pm}$, $K^{\pm}$, p, pbar) p_T spectra up to ~2 GeV/c boosted for increasing centrality, with a (mass-dependent) collective radial flow:



D.d'E, D.Peressounko EPJC 46(06)451

Strong radial collective flow built-up at freeze-out: $\langle\beta_T\rangle \approx 0.6$

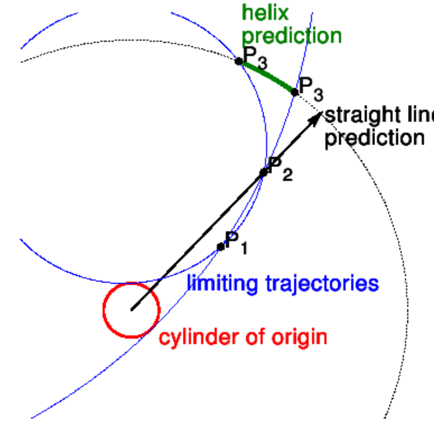


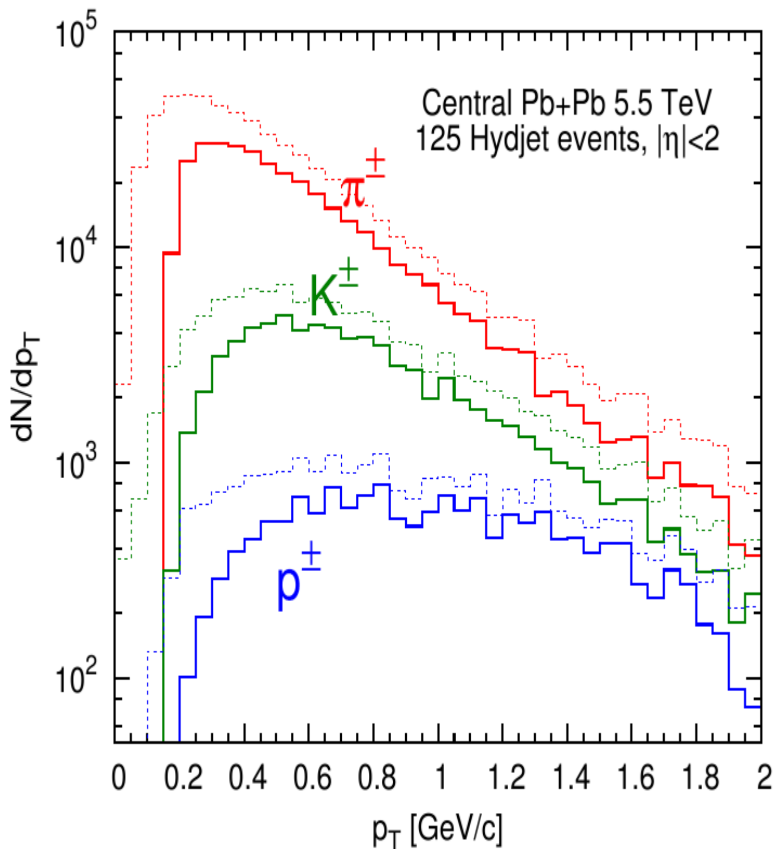
- "Explosive" behaviour well reproduced by hydrodynamics calculations w/ QGP Equation-of-State & fast thermalization times

Soft hadron spectra (CMS)

F.Sikler, CMS-AN06-100, AN06-101

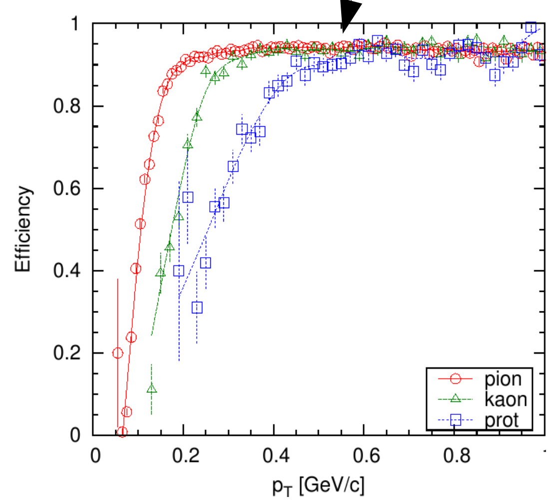
- Single hadron ($\pi^\pm$, $K^\pm$, p,pbar) p_T spectra in range p_T~ 0.2 – 2.0 GeV/c measurable w/ pixel-triplet algo in first 3 layers of Si tracker. PID via dE/dx (unfolding)

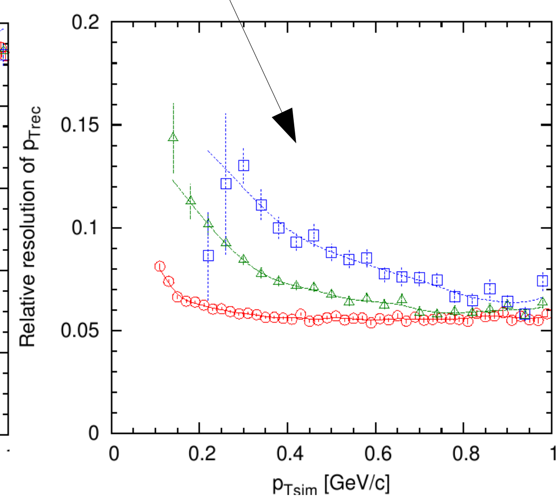




Above p_T~0.2 GeV/c:

accept./effic.~80-90%, p_T resol.~10%, fake rate<10%

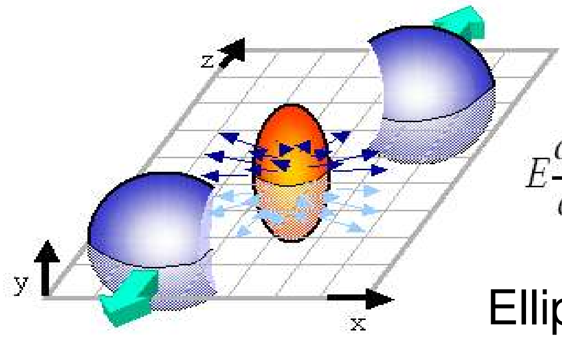




Case-Study III:
Elliptic flow

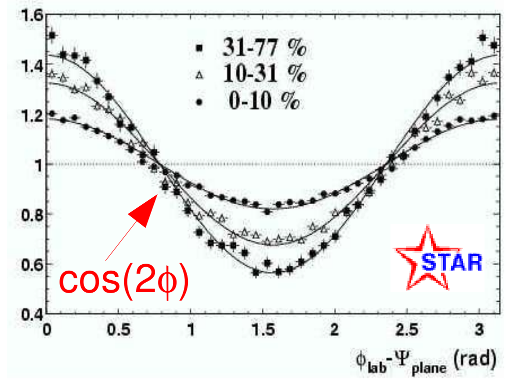
Elliptic flow (RHIC)

- Lens-shaped spatial anisotropy (overlap) in non-central collisions translates into boosted momentum emission along react. plane:

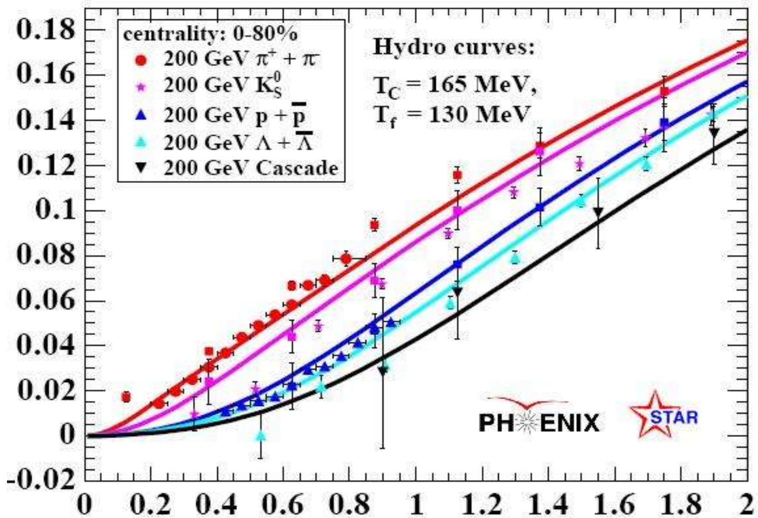


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos[n(\phi-\Phi_{RP})]\right)$$

Elliptic flow v_2 = 2[nd] Fourier coefficient



- Large v_2 signal (up to ~20%) for all hadrons (including $e^{\pm}$ from heavy-Q) well described by ideal hydrodynamics eqs. (but not by hadron/parton transport models):



⇒ Strong partonic pressure grads.

⇒ Large & fast parton rescattering: very fast thermalization.

⇒ Low viscosity (no "internal dissipation")

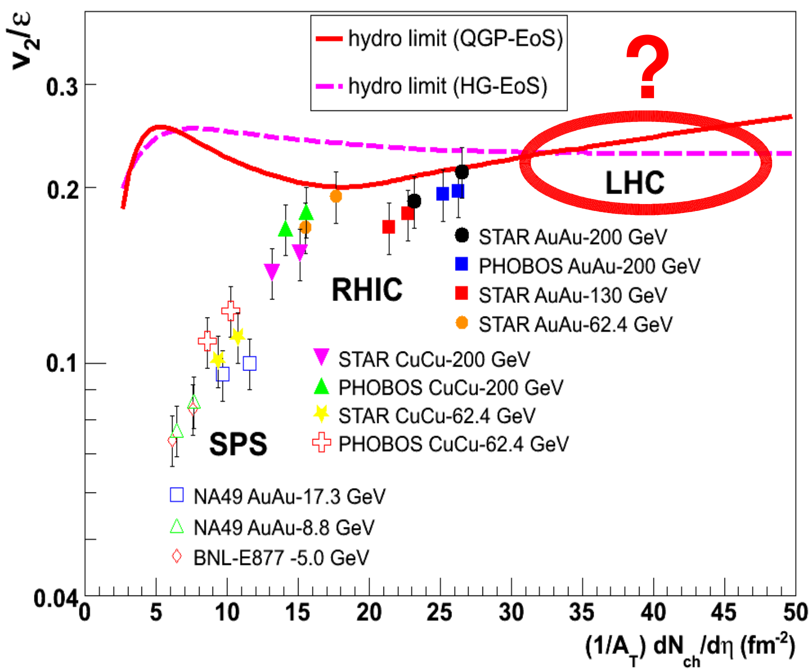
Elliptic flow (CMS)

I.Lokhtin et al., CMS-AN03-019, CMS-AN07-004

- LHC:

  null-viscosity fluid (RHIC) ?

  weakly interacting QGP ?



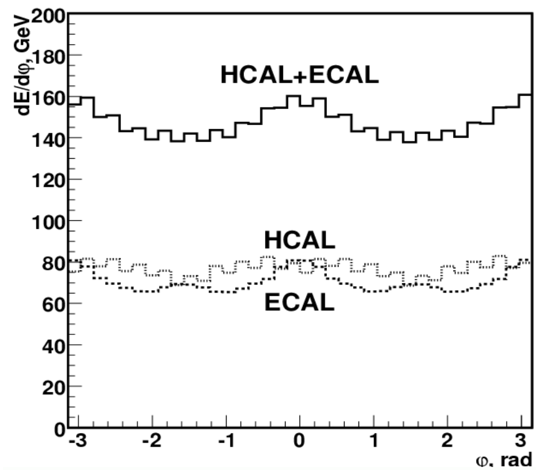
- 3 different methods :

(1) reaction-plane in HCAL+ECAL,

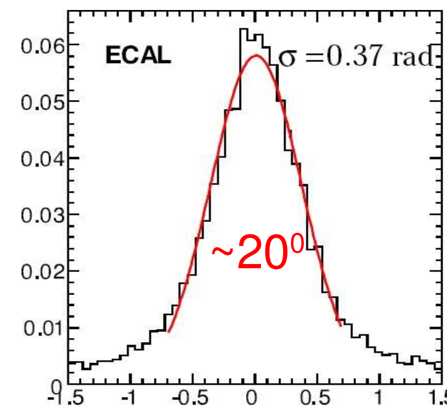
(2) reaction-plane in tracker,

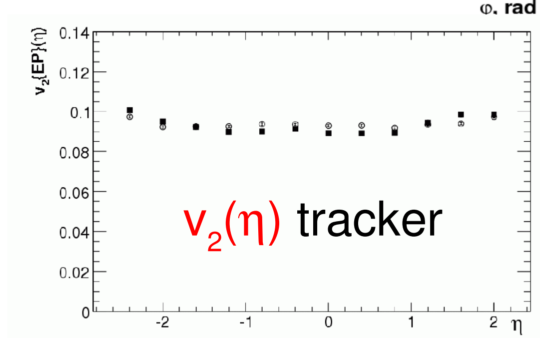
(3) cumulant analysis

v_2=0.12, Pb-Pb (b = 9 fm)



Good react-plane angle resolution



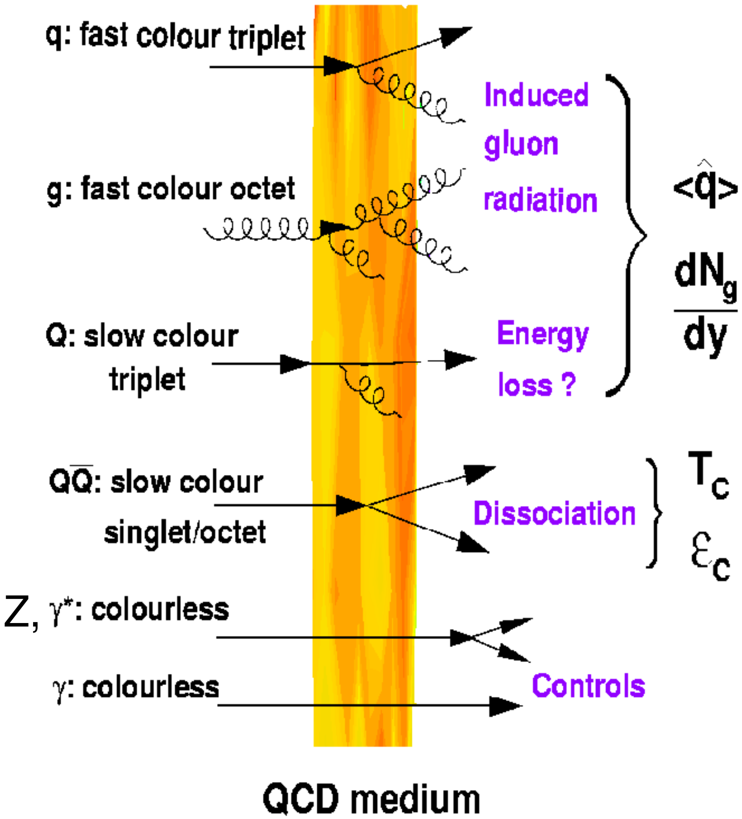


[Non-flow systematic uncertainties not included]

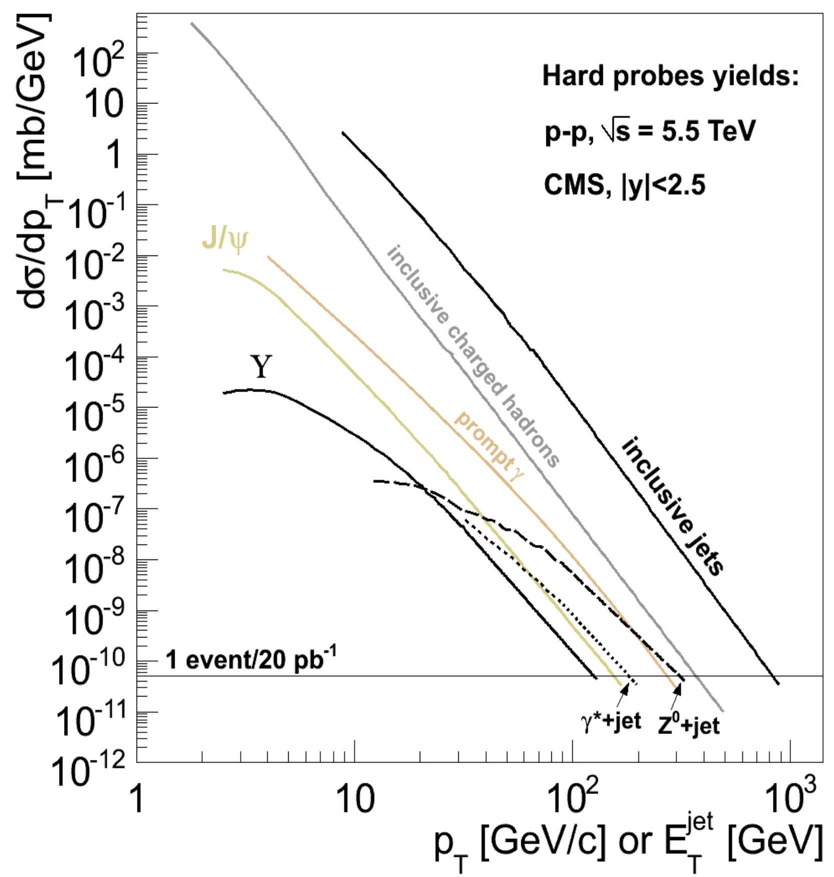
Case-Study IV:
Hard probes (triggering)

Hard probes in HE A-A collisions

- "E*xperimentally- & theoretically- controlled self-generated tomographic probes of the hottest and densest phases of AA collision*"
- Huge cross-sections at LHC. CMS designed to measure (& trigger) on them.



PbPb MB yields – CMS – 0.5 nb^{-1}



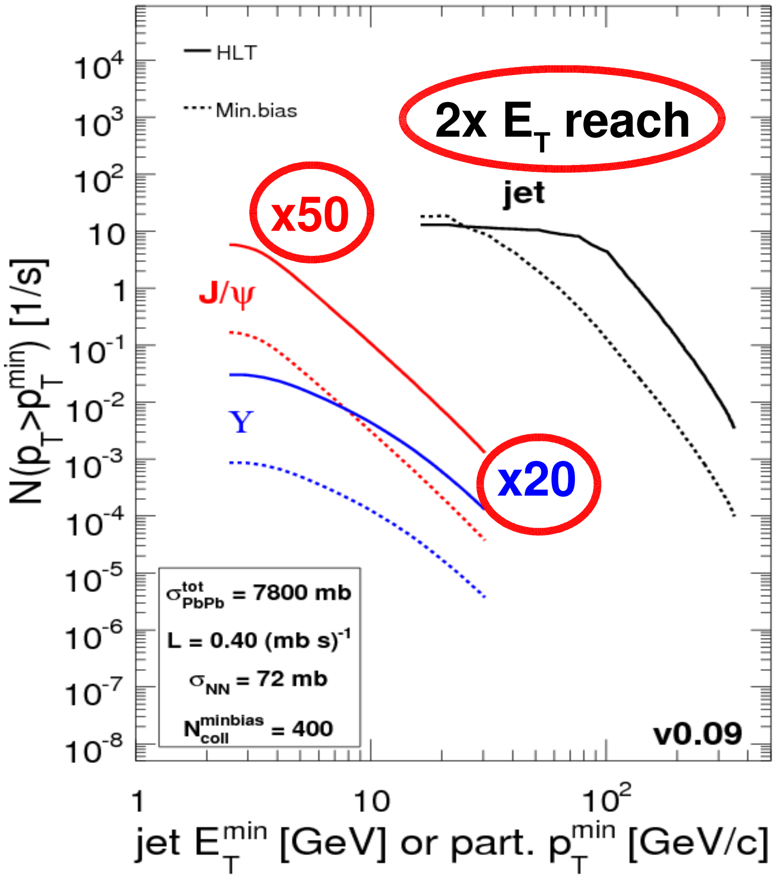
Hard probes (CMS) - High-Level Trigger

M.Ballitjin,C.Loizides,G.Roland, CMS-AN06-099

- Unique CMS High-Level-Trigger ≊ 12k × 1.8-Ghz CPUs ~ 50 Tflops !
- PbPb Luminosity: 10^{27} cm^{-2}s^{-1} (xA^2, pp-equivalent: $4\cdot10^{31}$ cm^{-2}s^{-1}, hard processes)
- PbPb ∫Luminosity (1-month, 50%): 0.5 nb^{-1} (pp-equivalent: ~20 pb^{-1})

- Event rates: 8 kHz (peak), 3 kHz (mean)
- L1 output [100 kHz pp design] >>PbPb rate
- Run HLT "offline" algos on every PbPb evt.

- Event size: ~9 MB (max), 2.5 MB (std.)
- Logging rate: 225 MB/s [10-100 Hz]
- HLT red. factor ~30
- HLT time-budget/evt. : ~4 s
- Significantly enhanced statistical reach for hard probes: x20 – x300



Case-Study V:
“Jet quenching”

"Jet quenching" (RHIC)

- Nuclear modification factor:

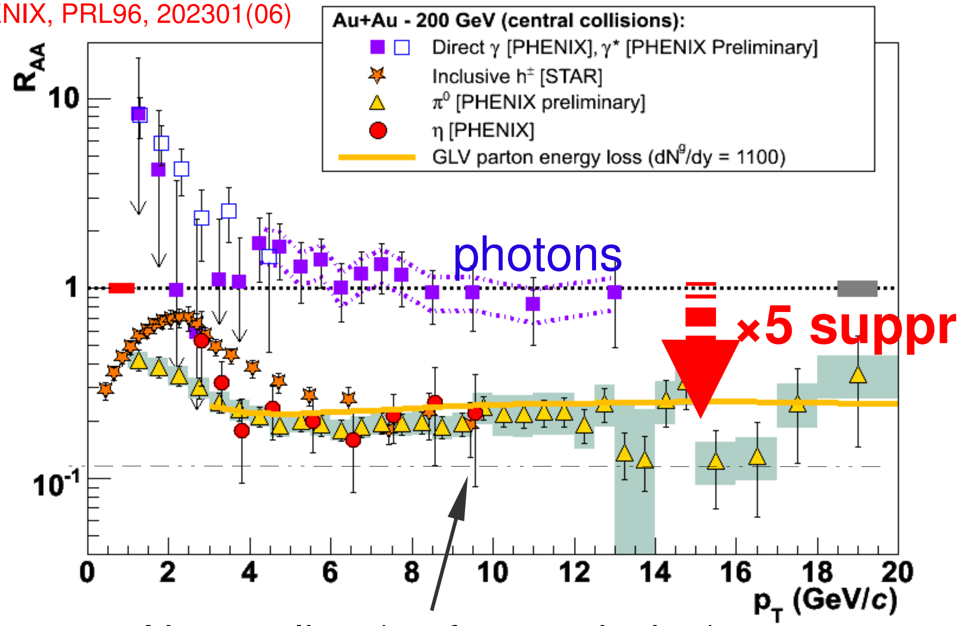
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AB}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T}$$

"QCD medium"/"QCD vacuum"

Initial medium density: $dN_g/dy \sim 1000$

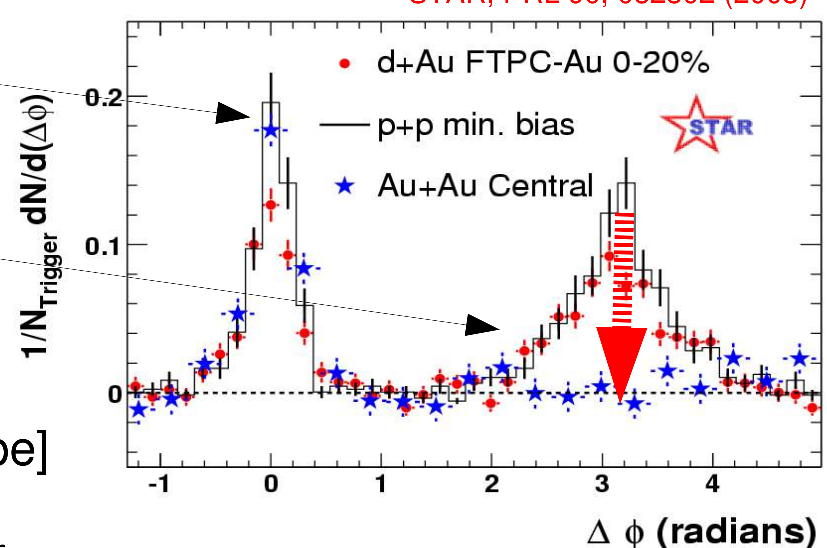
Transport coeffic.: $\langle\hat{q}\rangle \sim 14\ GeV^2/fm$

PHENIX, PRL96, 202301(06)



N_{part} scaling (surface emission)

STAR, PRL 90, 082302 (2003)

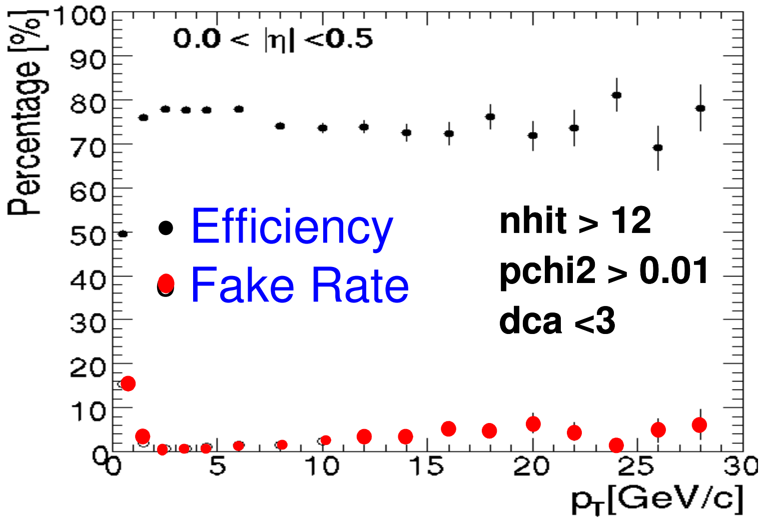


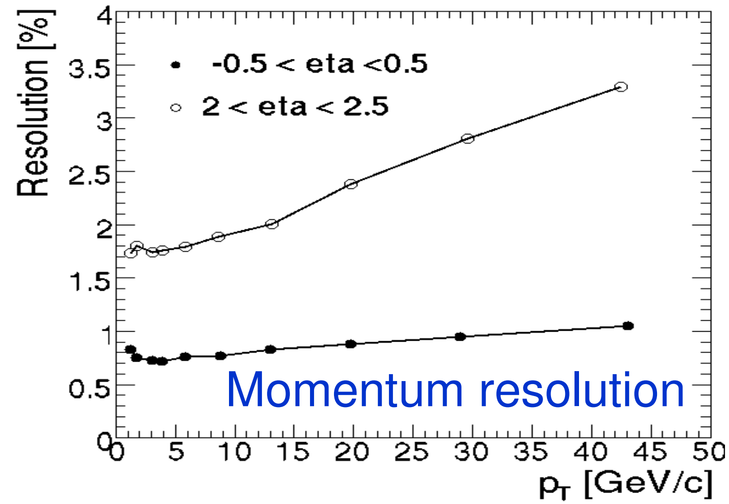
- Near-side jet-like Gaussian peak unmodified (AuAu ~ dAu ~ pp)
- Away-side peak disappears: "monojet"-like topology
- ["Lost" away-side energy dissipated at lower p_T values in conical-like shape]

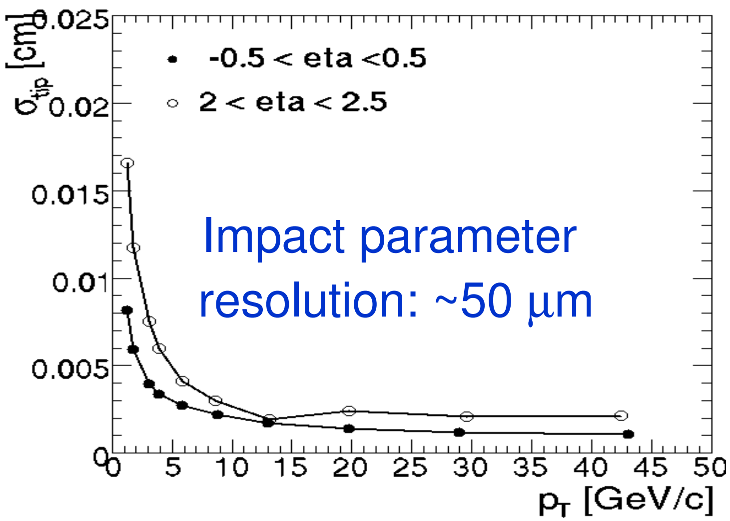
High-p_T (leading) charged hadrons (CMS)

C.Roland, CMS-AN06-001

- Excellent tracking performances (PbPb, $dN_{ch}/d\eta = 3500$):



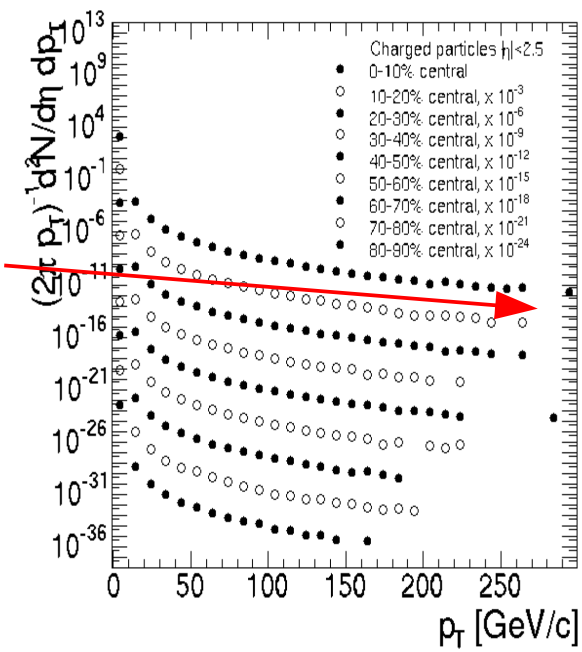




Expected dN/dp_T

reach p_T~300 GeV/c

(high E_T HLT)

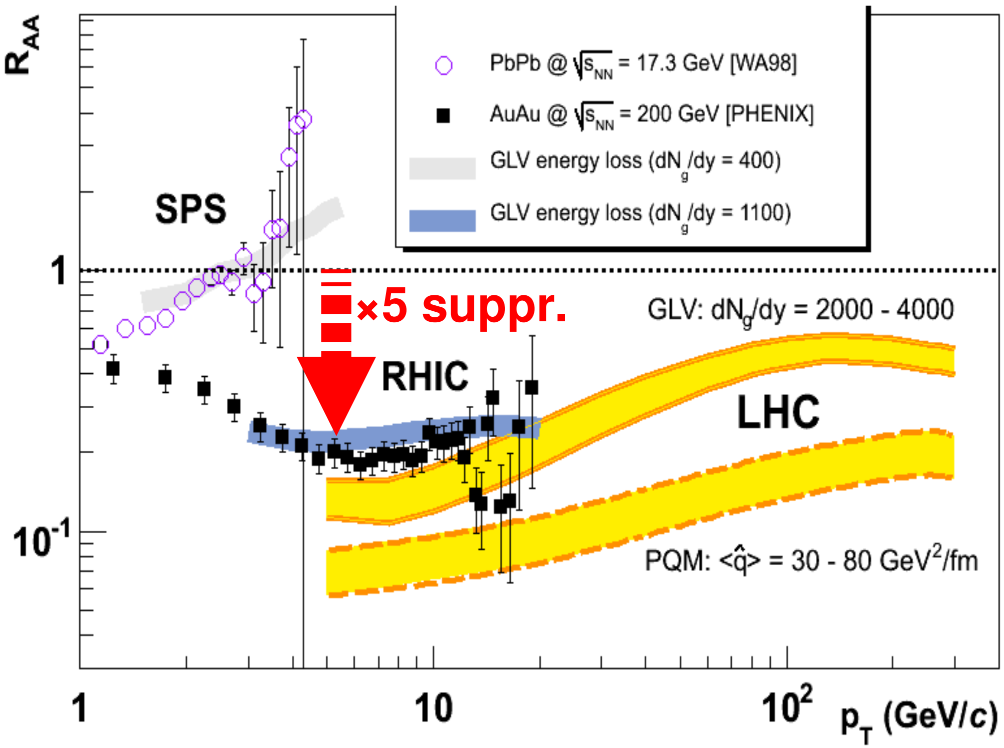


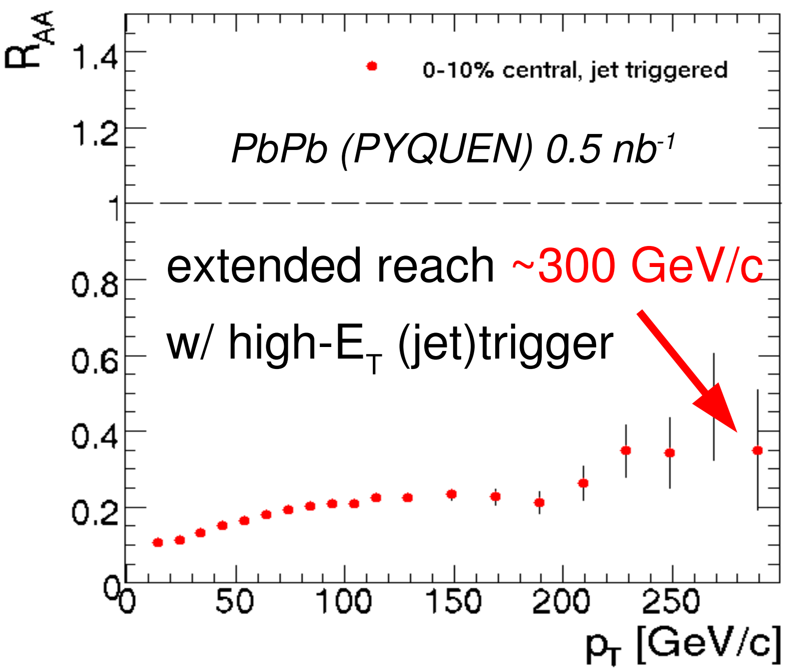
Displaced vertexes from heavy-Q decays measurable

High-p_T (leading) charged hadrons (CMS)

C.Roland et al., CMS-AN06-110

- Nuclear modification factor (= AA-yield / pp-yield) at the LHC:



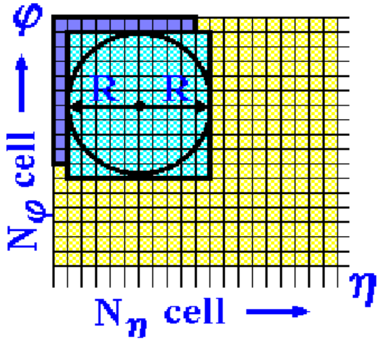


- Strong discrimination power for parton energy loss models:
  - Initial parton medium density: $dN_g/dy \sim O(2\text{-}4\cdot10^3)$
  - Medium transport coefficient: $\langle q \rangle \sim O(10\text{-}100)$ GeV²/fm

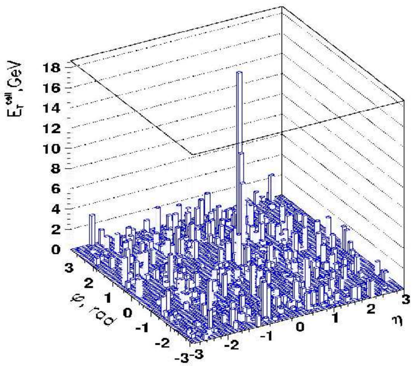
Pb-Pb full jet reconstruction (CMS)

I. Vardanyan et al. CMS-Note-2006-50

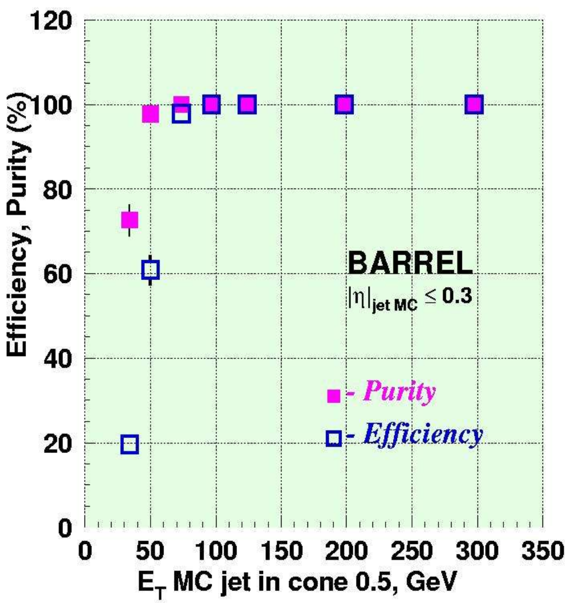
- Iterative-cone + backgd subtraction. [New developments (fastJet) under study]



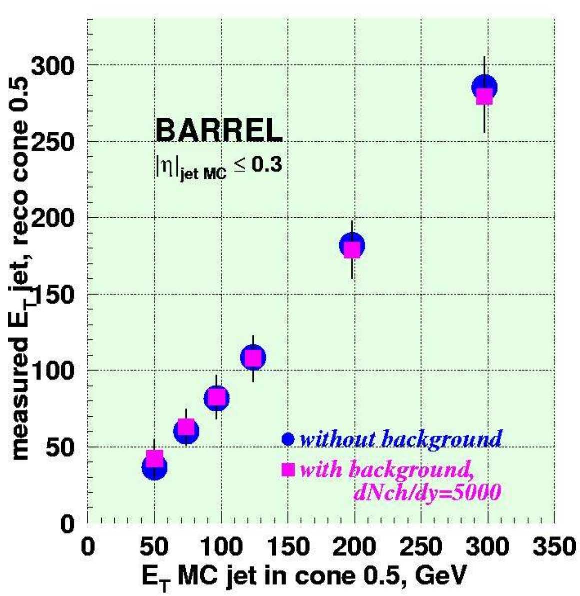
1. Subtract average soft background
2. Find jets: iterative cone algorithm
3. Recalculate pileup outside cone
4. Recalculate jet energy



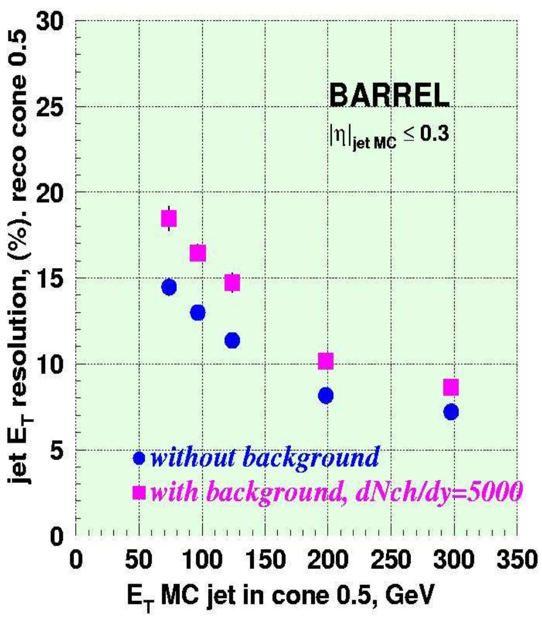
efficiency, purity



jet energy: reco vs. MC



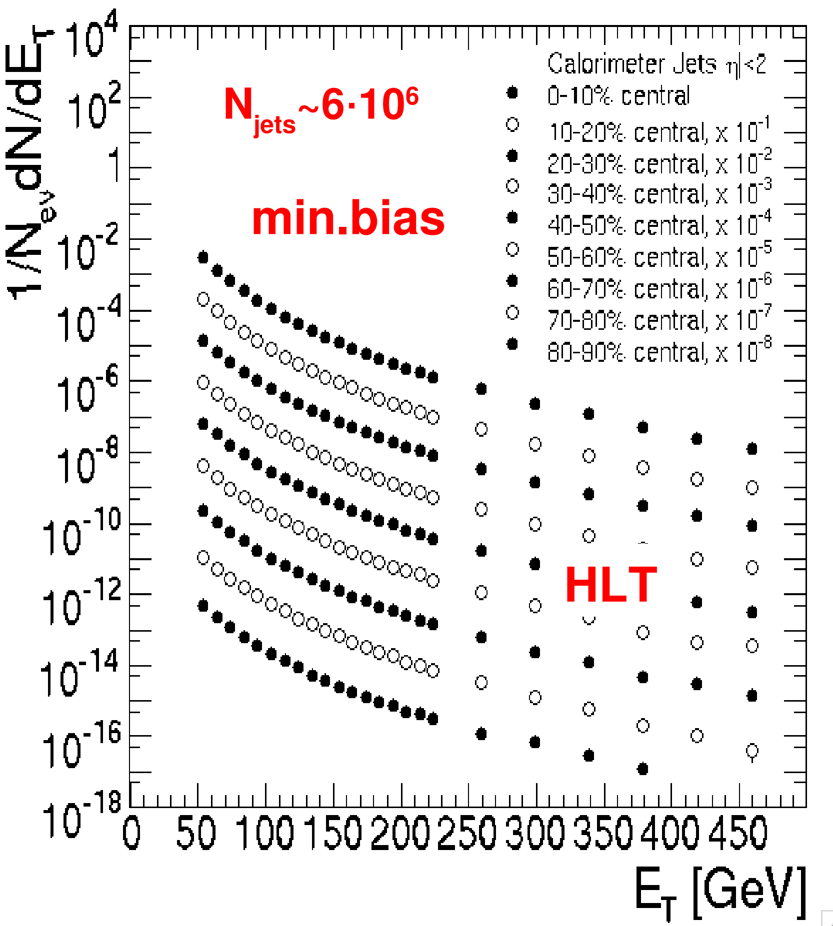
energy resolution

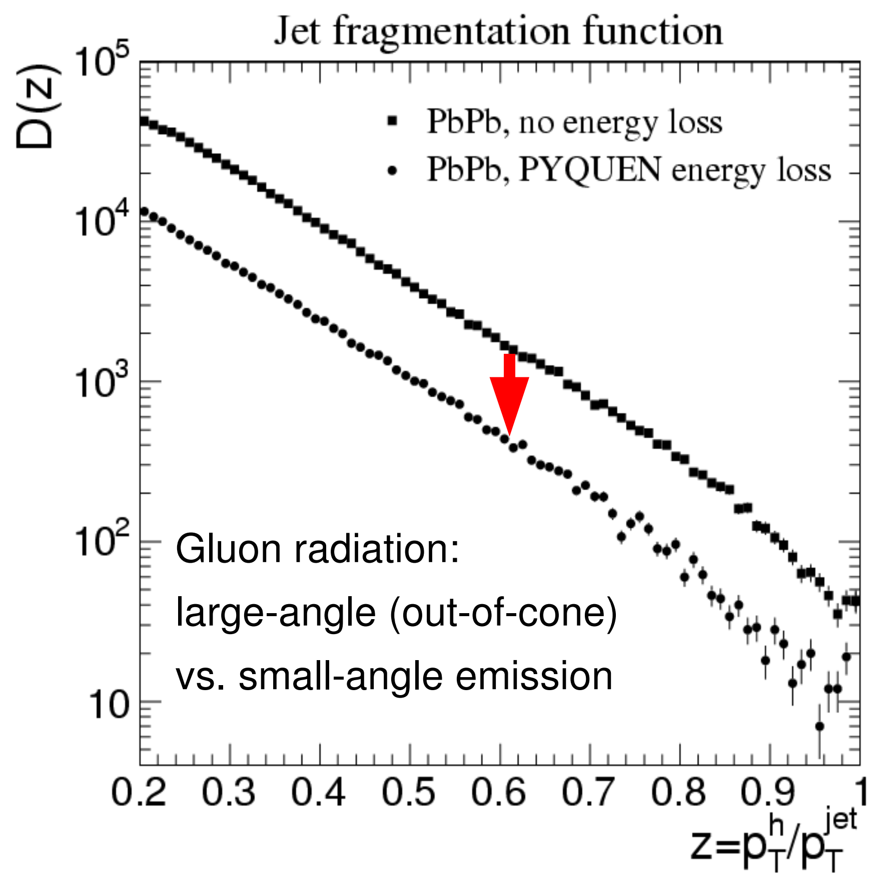


Pb-Pb full jet reconstruction (CMS)

C.Roland et al., CMS-AN06-110

- Jet spectra up to E_T~ 0.5 TeV (PbPb, 0.5 nb^{-1}, HLT-triggered).
- Detailed studies of medium-modified (quenched) jet FF possible.



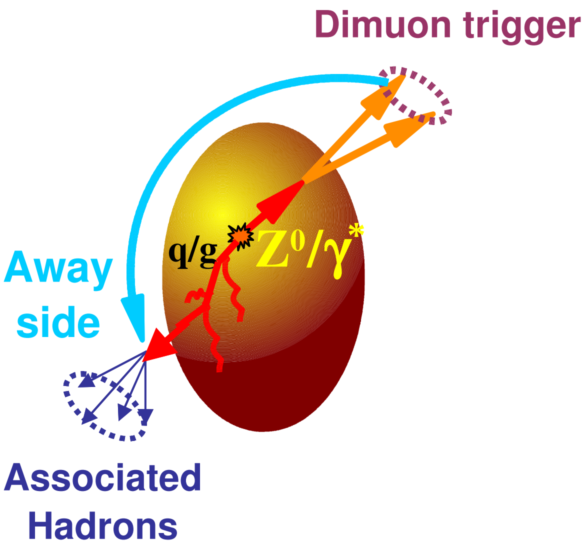


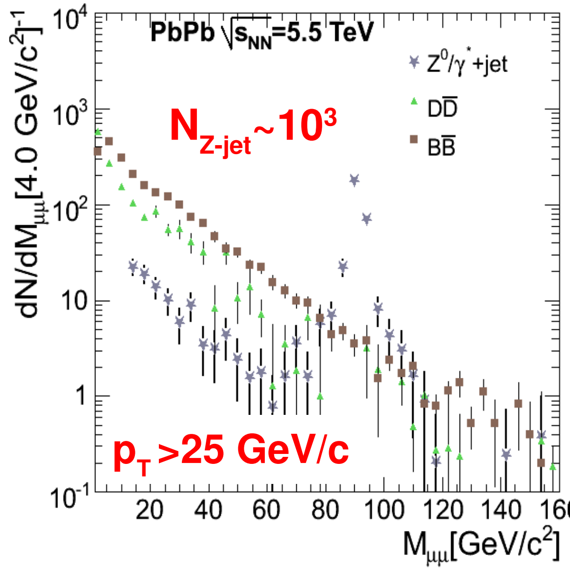
I. Lokhtin et al., PLB567 (03)39

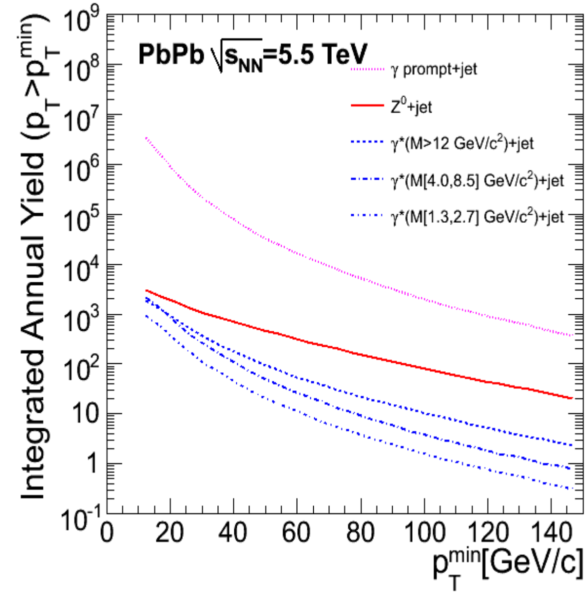
γ– , γ*– , Z– jet tagging (CMS)

C.Mironov et al., CMS-Note07-xx

- Possibility to calibrate jet-energy loss (and FF) with back-to-back gauge boson (large cross-sections, good detection capabilities):



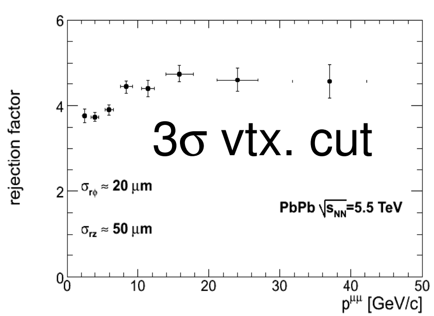


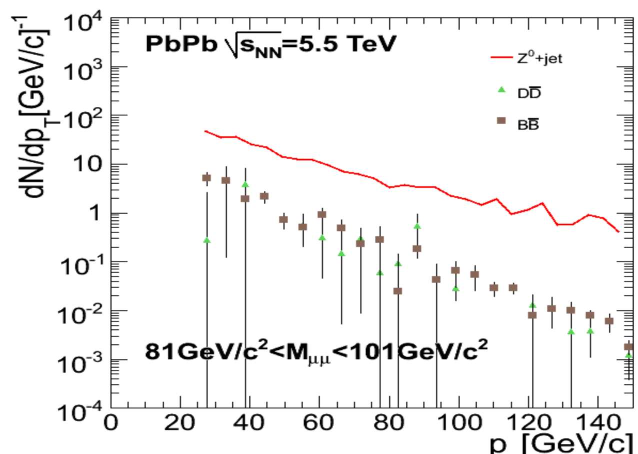


- Dominant (heavy-Q) dimuon backgd. "removable" via secondary-vtx. cut

σ_r=50 μm

σ_φ=20 μm

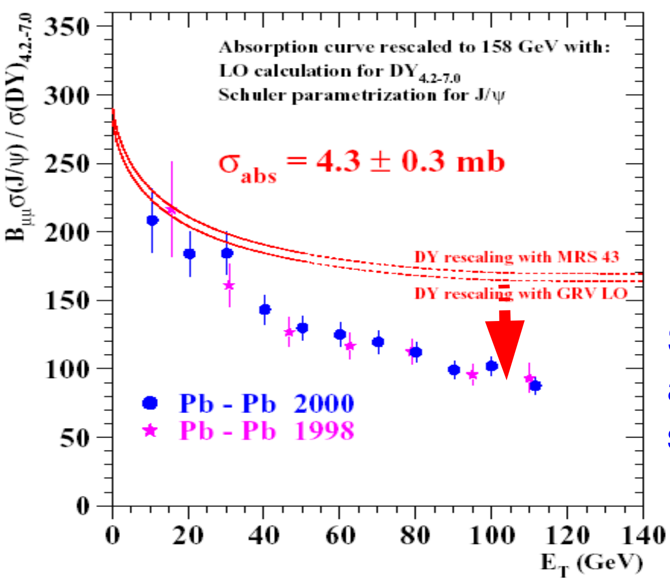




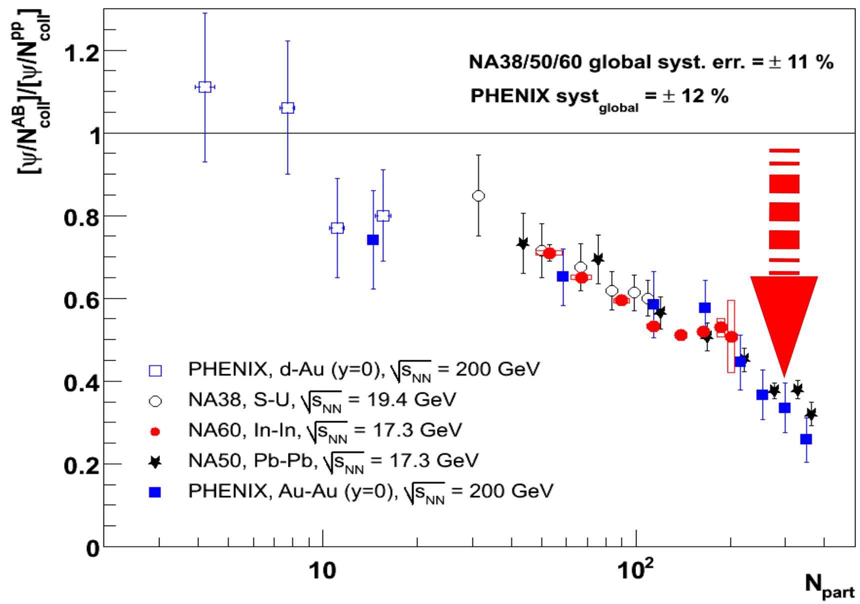
Case-Study VI: Quarkonia suppression

J/ψ suppression (SPS, RHIC)

- J/ψ suppression vs. centrality (N_{part}):



SPS NA50 anomalous suppression



- Same suppression observed at RHIC (T~400 MeV) & SPS (T~200 MeV) !?

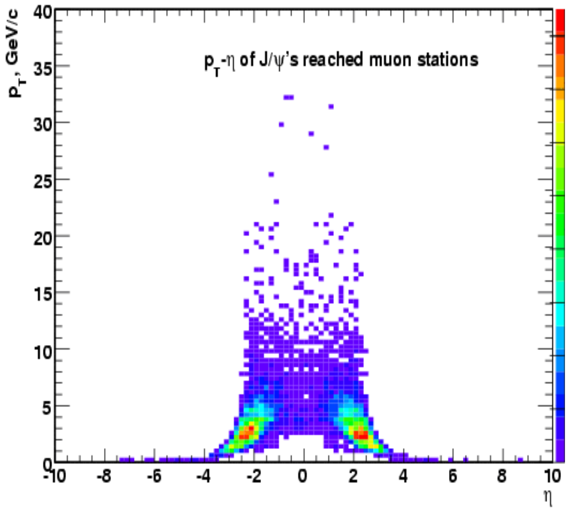
Recombination: ccbar regeneration (~10 ccbar pairs in central AuAu) compensates for screening

Sequential dissociation: Only ψ' and χ_c (~40% feed-down J/ψ) suppressed. Direct J/ψ survives at RHIC ⇒ $T_0 <\sim 2 \cdot T_c$

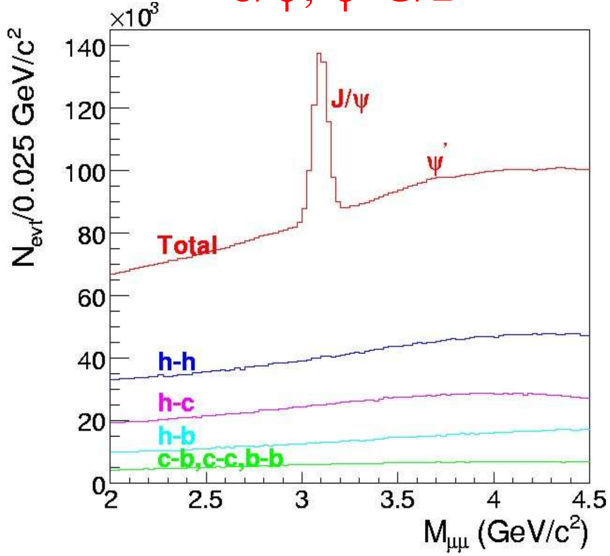
J/ψ suppression (CMS)

O.Kodolova, M. Bedjidian, CMS-AN06-116

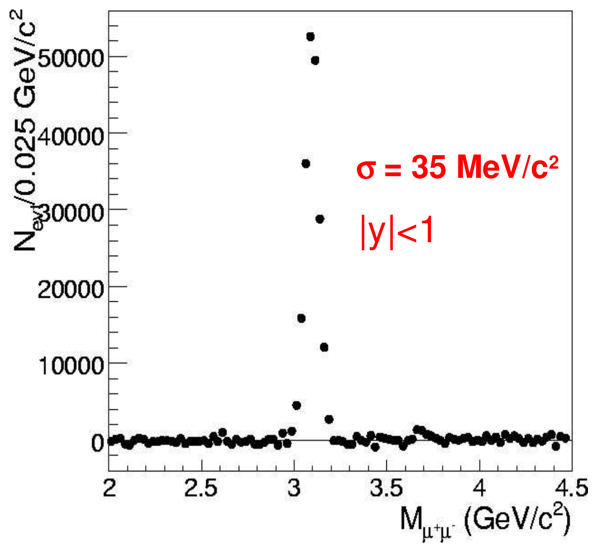
J/ψ acceptance

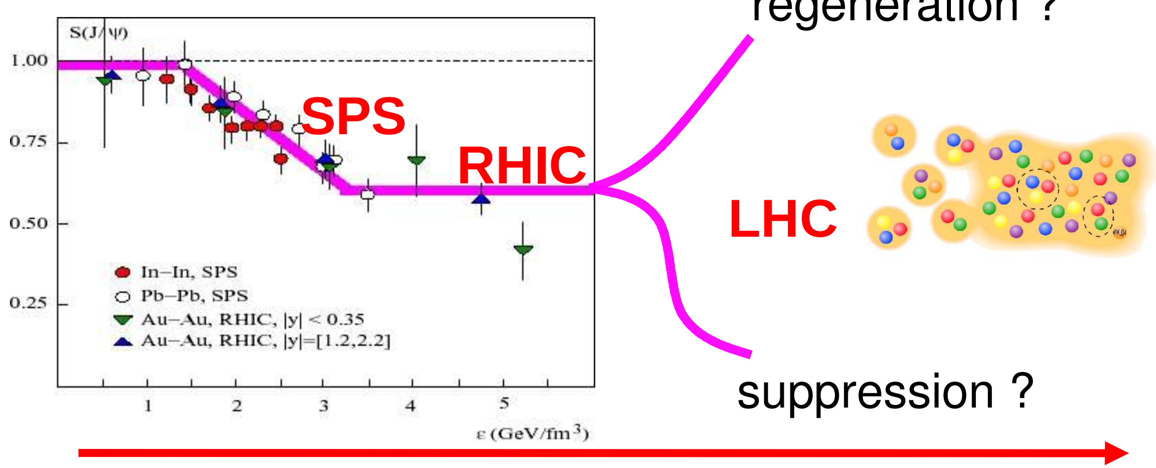


J/ψ, ψ' S/B

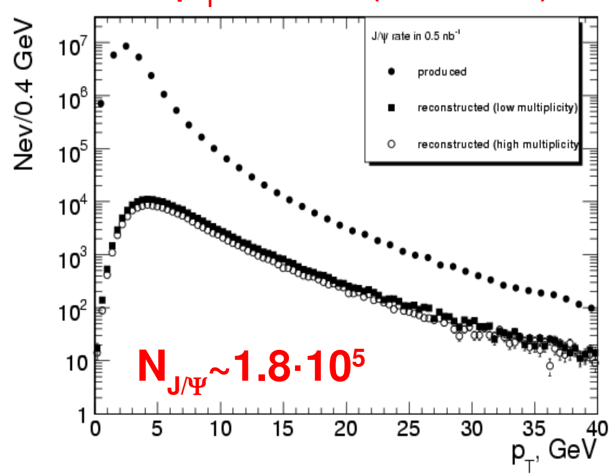


Best mass resolution @ LHC





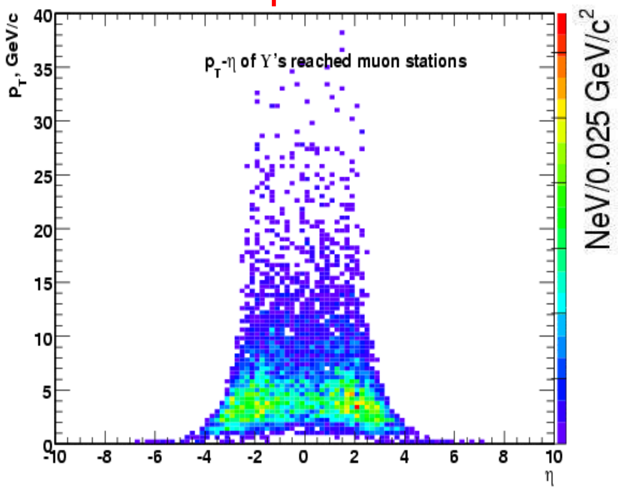
p_T reach (0.5 nb^{-1})



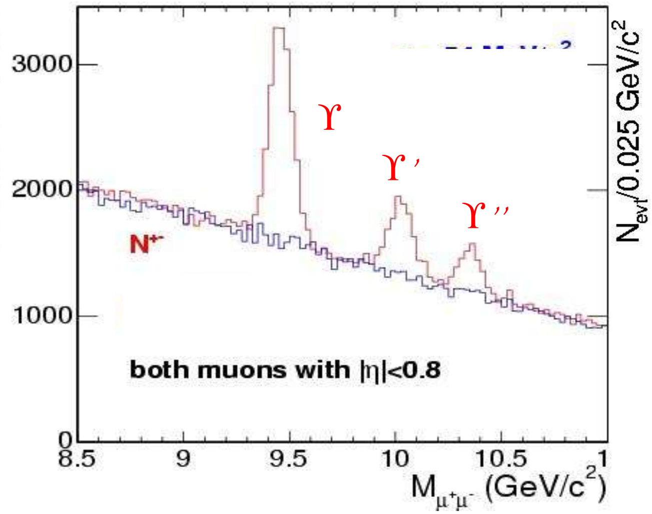
ϒ suppression (CMS)

O.Kodolova, M. Bedjidian, CMS-AN06-116

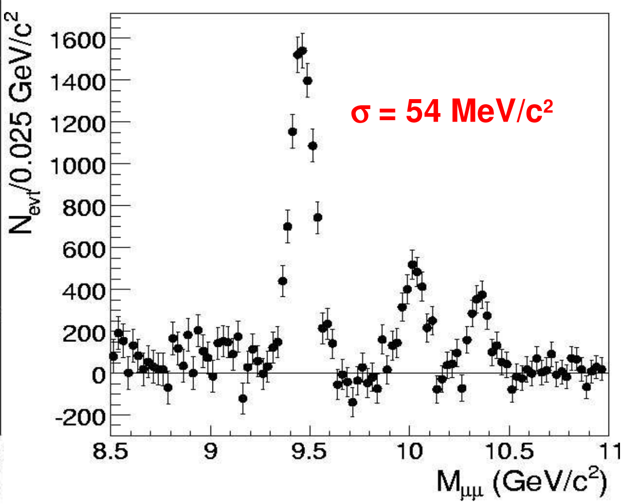
ϒ acceptance



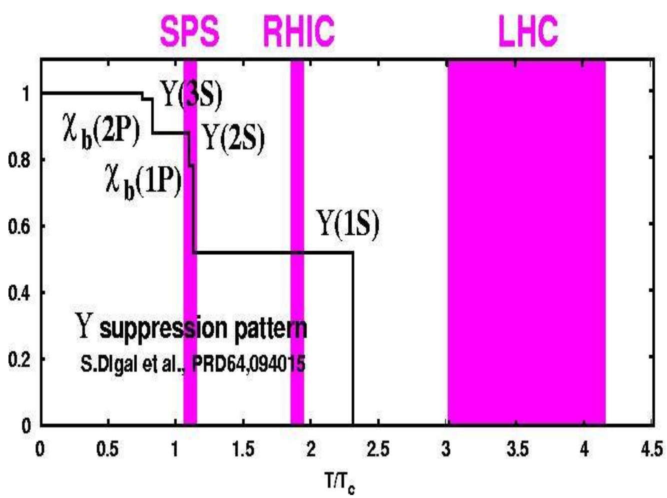
ϒ family S/B



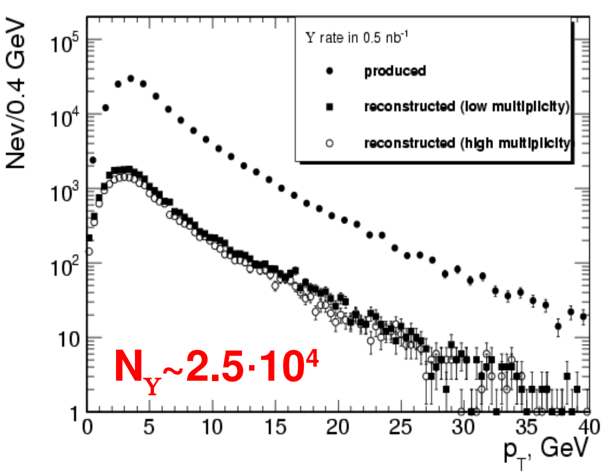
Best mass resolution @ LHC



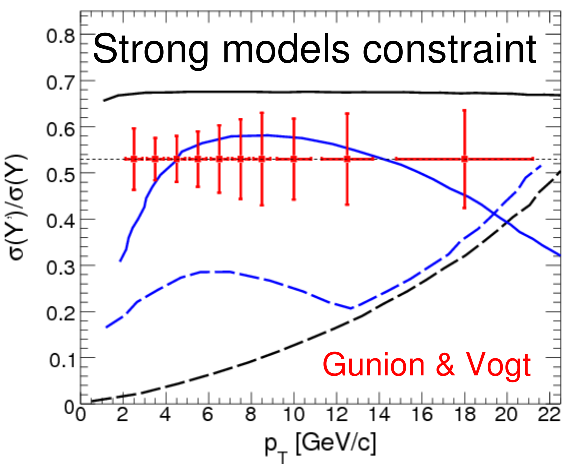
ϒ spectroscopy (seq. suppr.)



p_T reach (0.5 nb^{-1})



ϒ′/ϒ stat. reach (HLT)

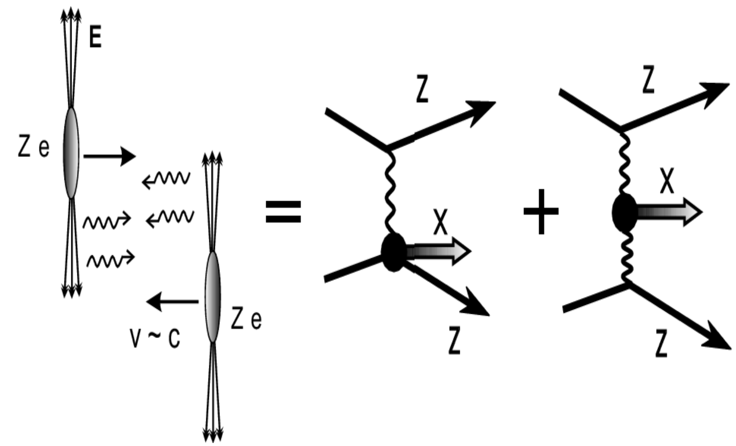


Case-Study VII:
Low-x nuclear PDF

Low-x $xG(x,Q^2)$ via UPC γ Pb→ϒ+X

Dd'E, A.Hees, CMS-AN06-107

- High energy heavy-ions produce strong electromagnetic fields due to the coherent action of $Z = 82$ protons:



- Equivalent flux of photons in EM (aka. UltraPeripheral, $b_{min} \sim 2R_A \sim 20$ fm) AA colls.:

  Max. γ energy: $E_{\gamma max} \sim 80$ GeV (PbPb-LHC)

  γ Pb: max. $\sqrt{s_{\gamma Pb}} \approx 1.$ TeV $\approx 3. - 4. \times \sqrt{s_{\gamma p}}$(HERA)
  $\gamma\gamma$: max. $\sqrt{s_{\gamma\gamma}} \approx 160$ GeV $\approx \sqrt{s_{\gamma\gamma}}$ (LEP)

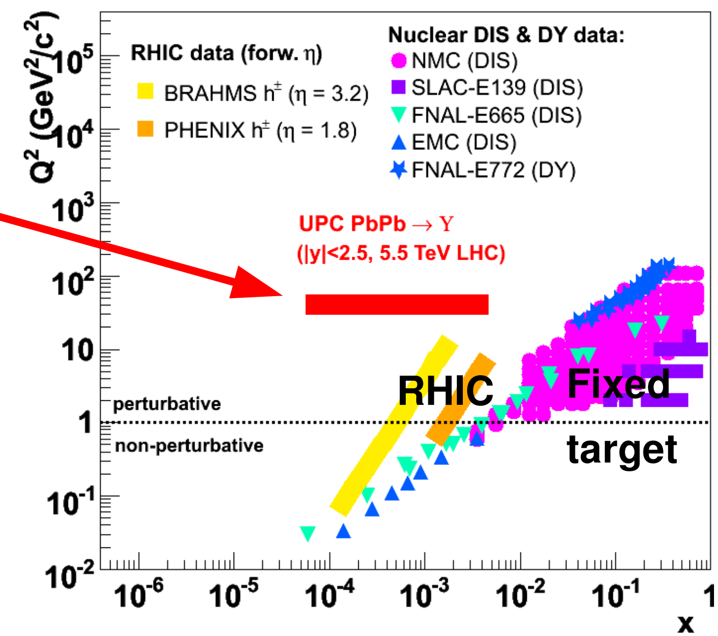
- Unexplored (x,Q^2) regime in the nucleus

  Gluon saturation – non-linear QCD ⇒

  Suppressed hard photoproduction.

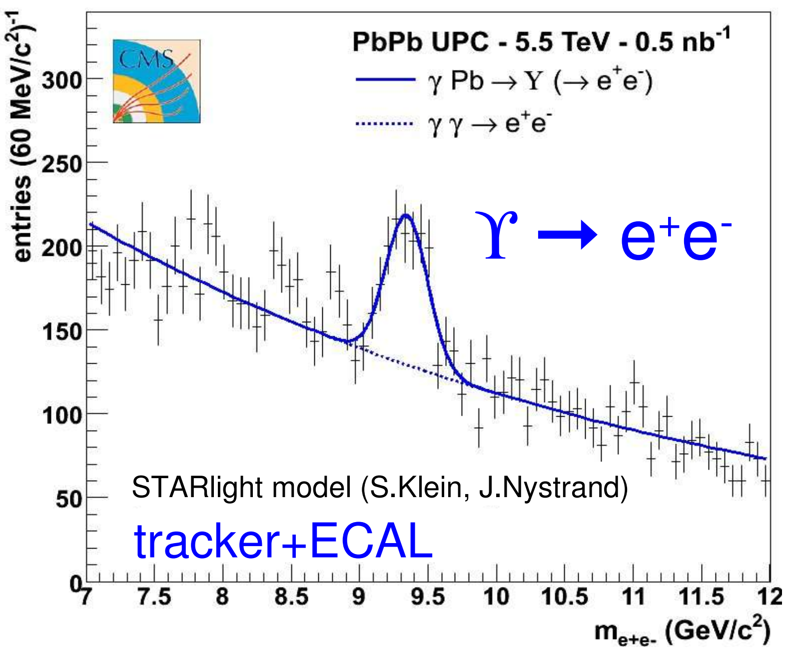
  $y=0 : x(\Upsilon) = 2\cdot 10^{-3}$

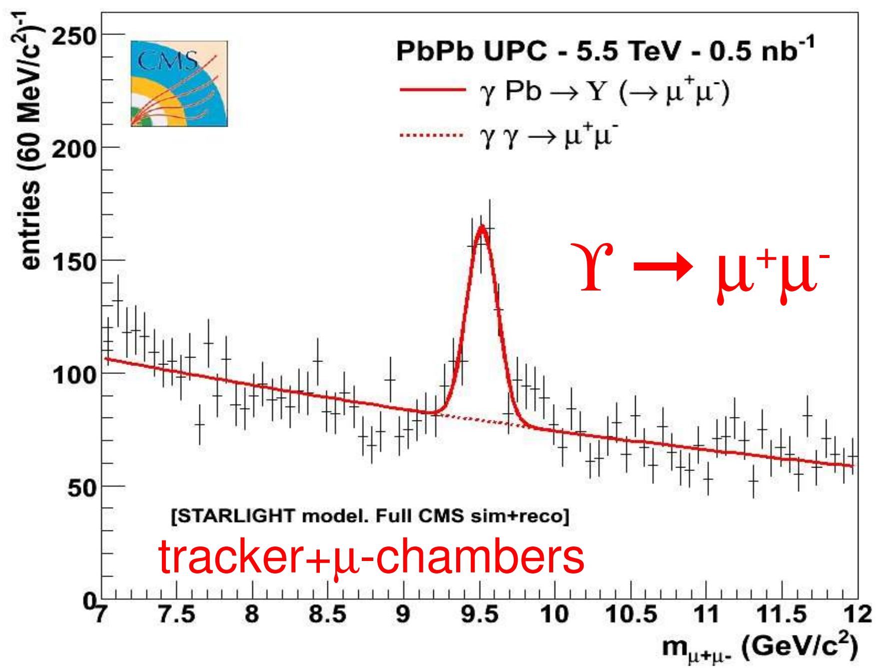
  $y\sim 2 : x(\Upsilon) \sim x(y=0)\cdot e^{-y} \sim 10^{-4}$



γ Pb→Υ+X: Full sim+reco (CMS)

- Full CMS gen+sim+digi+hit+reconstruction: D.d'E. QM'06. JPG. hep-ex/0703024





Peak position: ~9.35 GeV/c^2

Mass resolution: ~150 MeV/c^2

Peak position: ~9.52 GeV/c^2

Mass resolution: ~90 MeV/c^2

- Excellent $\mu\mu$ mass resolution: higher mass $\bar{b}b$ states (Υ',Υ'') can be resolved (not in MC now)
- Enough stats (N~500) for detailed studies (including y-dependence) of gluon PDF

Summary

- CMS has excellent PbPb, pPb, pp detection capabilities:

  - charged tracks, muons, electrons/photons within $|\eta| < 2.5(3.0)$, full φ
  - jets, particle/energy flow within $|\eta| < 6.7$ (and $\eta > 8.1$, neutral), full φ
  - excellent precision/granularity/resolution
  - large bandwidth DAQ / very powerful HLT

- CMS is complementary to ALICE & very competitive in most relevant physics observables in PbPb @ 5.5 TeV at the LHC:

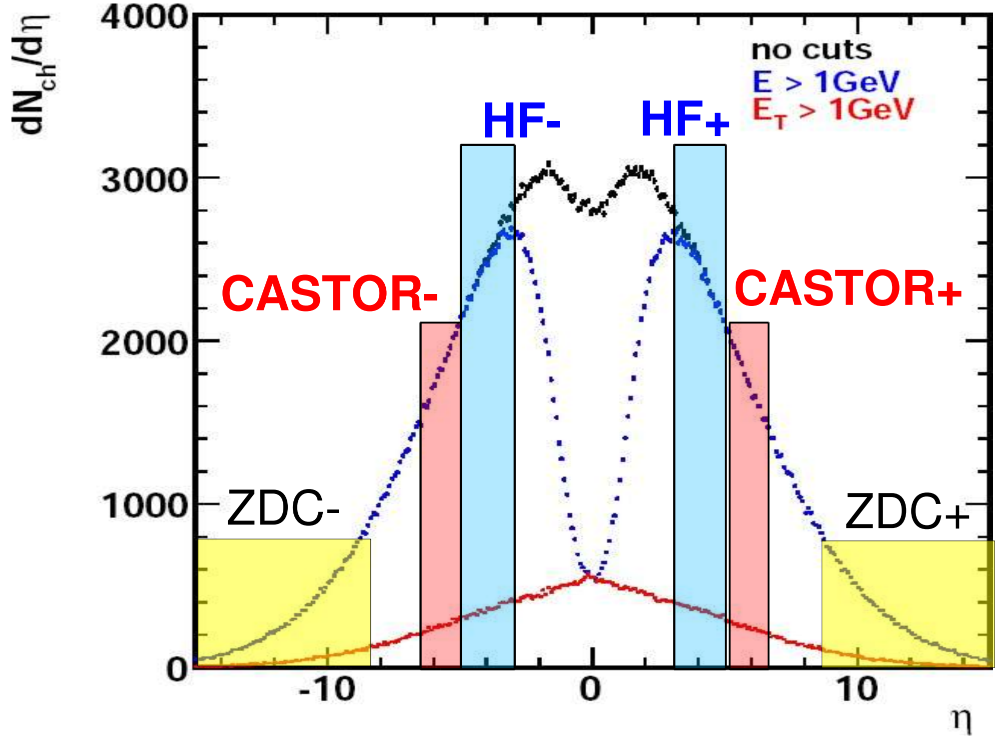
  - Case I: $dN_{ch}/d\eta \Rightarrow$ Colour-Glass-Condensate
  - Case II: Low p_T π/K/p spectra [p_T~0.2 – 2. GeV/c] $\Rightarrow$ Hydrodynamics, Equation-of-State
  - Case III: Elliptic flow $\Rightarrow$ Hydrodynamics, Medium viscosity
  - Case IV: Hard-probes [triggering] $\Rightarrow$ Thermodyn. & transport properties
  - Case V: "Jet quenching" [E_T~0.5 TeV,p_T^h~300 GeV/c] $\Rightarrow$ Parton density, $\langle\hat{q}\rangle$ transp. coeff.
  - Case VI: QQbar suppression [$N_{J/\Psi}$~2e+5, N_Υ~2e+4] $\Rightarrow \varepsilon_{crit}$, T_{crit}
  - Case VII: $\Upsilon \rightarrow e^+e^-,\mu^+\mu^-$ photoproduction in UPC PbPb [N_Υ~500] $\Rightarrow$ Gluon $xG_A(x,Q^2)$

Backup slides

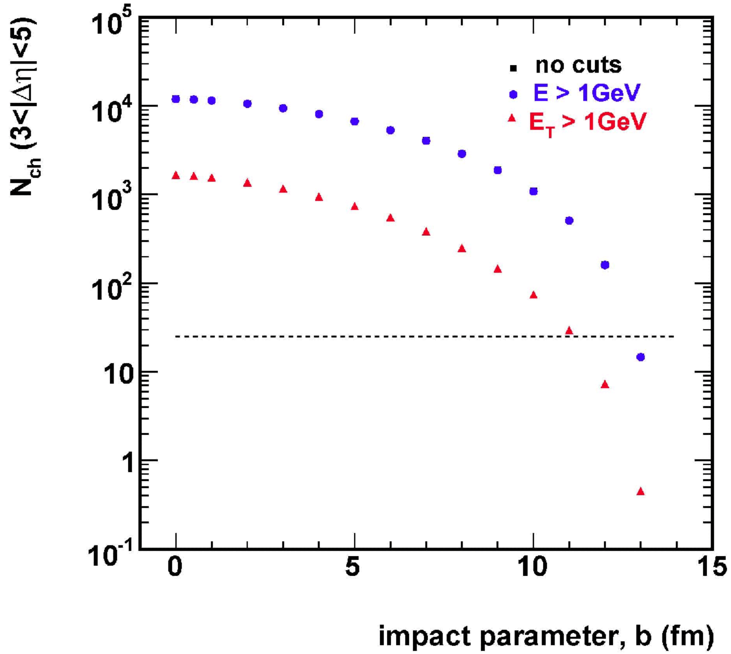
Case-Study 0:
MB trigger, Pb-Pb centrality

Pb-Pb L1 minimum-bias trigger

- HF^{+}.AND.HF^{-} (+ZDC) = default L1 MB (interaction) PbPb trigger



Large efficiency up to very peripheral (grazing) PbPb colls.



- NB: $CASTOR^{+}$.AND.$CASTOR^{-}$ (+ZDC as done at RHIC) should provide more "genuine" minimum bias events (with reduced hard QCD activity).

Pb-Pb reaction centrality

- Centrality = crucial parameter to determine PbPb collision overlap: volume, particle/energy density of “fireball”.
- E_{tot},E_T in CASTOR or HF = monotonic functions of impact parameter (b)

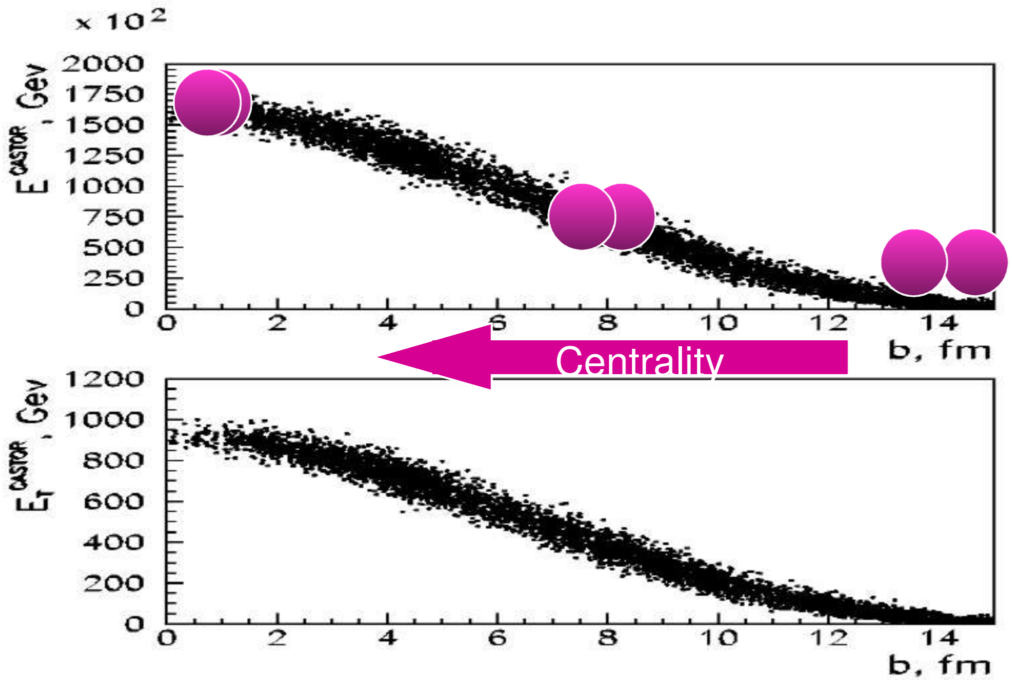
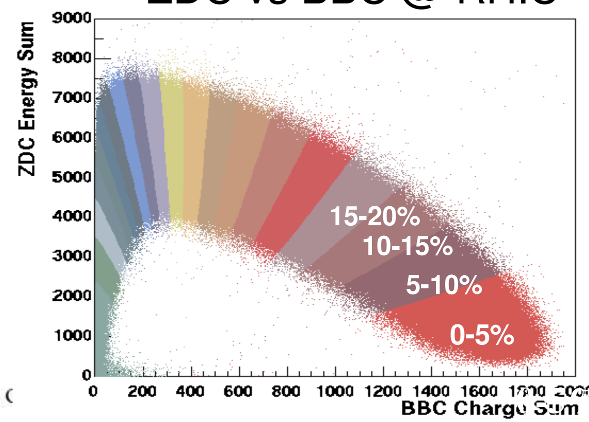


Figure 3: The distributions of energy and transverse energy deposited in CASTOR as a function o
the impact parameter, b, for the highest energy Pb-Pb collisions at the LHC.

ZDC vs BBC @ RHIC



- NB: Correlation of CASTOR E_{tot} with ZDC E_{tot} will provide yet more accurate determination of the event centrality (default method at RHIC).